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Ground-Water-Withdrawal Component of the Michigan Water-Withdrawal Screening Tool

Scientific Investigations Report 2009–5003

U.S. Department of the Interior
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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
meter (m)	3.281	foot (ft)
mile (mi)	1.609	kilometer (km)
kilometer (km)	0.6214	mile (mi)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
gallon per minute (gal/min)	3.785	liter per minute (L/min)
gallon per day (gal/d)	4.3×10^{-8}	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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Ground-Water-Withdrawal Component of the Michigan Water-Withdrawal Screening Tool

By Howard W. Reeves[1], David A. Hamilton[2], Paul W. Seelbach[3], and A. Jeremiah Asher[4]

Abstract

A water-withdrawal assessment process and Internet-based screening tool have been developed to evaluate proposed new or increased high-capacity water withdrawals in Michigan. Michigan legislation defines high capacity withdrawals as those capable of removing an average of 100,000 gallons per day for a consecutive 30-day period. This report describes the ground-water component of the screening tool, provides background information used to develop the screening tool, and documents how this component of the screening tool is implemented. The screening tool is based on application of an analytical model to estimate streamflow depletion by a proposed pumping well. The screening tool is designed to evaluate intermittent pumping, to account for the dynamics of stream-aquifer interaction, and to apportion streamflow depletion among neighboring streams. The tool is to be used for an initial screening of a proposed new or increased high-capacity withdrawal in order to identify withdrawals that may cause adverse resource impacts. The screening tool is not intended to be a site-specific design tool. Results of an example application of the screening tool in Kalamazoo County, Mich., are compared to streamflow depletion estimated by use of a regional ground-water-flow model to demonstrate its performance.

Introduction

The water-withdrawal assessment process mandated by State of Michigan Public Act 34 of 2006 (2006 PA 34) (Michigan State Legislature, 2006a) was proposed to "assist in determining whether the proposed [water] withdrawal may cause an adverse impact to the waters of the state or to the water-dependent natural resources of the state." The water-withdrawal assessment process was developed under the auspices of the Michigan Ground Water Conservation Advisory Council (GWCAC), which was formed though Public Act 148 of 2003 (2003 PA 148) (Michigan State Legislature, 2003) and revised by 2006 PA 34. In response to 2006 PA 34, the U.S. Geological Survey (USGS) entered into a cooperative agreement in 2006 with the Michigan Department of Natural Resources; the Michigan Department of Environmental Quality; the Institute for Fisheries Research, University of Michigan; and the Institute for Water Research, Michigan State University, to assist in developing the technical aspects of the water-withdrawal assessment process.

The 2006 PA 34 legislation presumed that, for the first 2 years of the act, wells deeper than 150 ft or further away than ¼-mi from trout streams did not create an adverse resource impact on a trout stream (Michigan State Legislature, 2006a). Wells within ¼-mi of a trout stream and less than 150 ft deep may have posed an adverse resource impact on the stream, but the legislation did not specify how this potential should be analyzed. This presumption expired in 2008, and the legislature replaced it with the water-withdrawal assessment process including an Internet-based screening tool (Public Act 185 of 2008 (2008 PA 184), Michigan State Legislature, 2008a). The water-withdrawal process identifies withdrawals likely to cause an adverse environmental impact on the waters of the State by assessing whether the withdrawal will affect the ability of a stream to support the characteristic fish population at a site (State of Michigan Ground Water Conservation Advisory Council, 2007).

Assessment Process and Screening Tool

The legislature and GWCAC envisioned a screening tool as part of the water-withdrawal assessment process. In this report, the term "assessment process" refers to the entire process used to assess a new or increased high-capacity withdrawal from surface water or ground water, including initial screening, site-specific review, and agency procedures. High capacity withdrawals are defined through legislation as those capable of removing an average of 100,000 gal/d for a

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consecutive 30-day period (as defined in section 32701 of Public Act 33 of 2006 (2006 PA 33), Michigan State Legislature, 2006b). The screening tool is an Internet-accessible program used for an initial screening of a proposed new or increased high-capacity withdrawal. This screening tool identifies withdrawals that are not likely to cause an adverse resource impact upon any type of stream in the State and allows users proposing such withdrawals to proceed with the withdrawal after registering the use. Withdrawals identified as having potential to cause an adverse resource impact are expected to require additional agency review to determine their disposition (State of Michigan Ground Water Conservation Advisory Council, 2007). This tool is designed to focus regulatory resources on withdrawals that have greater potential to cause environmental harm. The screening tool uses a statewide database of aquifer types and properties in conjunction with a robust analytical equation to identify withdrawals not likely to cause an adverse environmental impact.

In this report, the component of the screening tool used to estimate the amount of streamflow reduction caused by a given ground-water withdrawal is presented and discussed. The complete screening tool, including ground-water and surface-water withdrawals and the decision rules used to evaluate withdrawals, will be documented in a separate report.

Streamflow Depletion by Pumping Wells

The key to understanding the potential impact of a pumping well on streamflow is to recognize the source of water to wells as described, for example, by Theis (1940), Bredehoeft and others (1982), Sophocleous (1997), Alley and others (1999), and Bredehoeft (2002). When a well is pumped, water is removed initially from storage in the aquifer, and the potentiometric level, or head, near the well is reduced. Once the head near the well is reduced, then flow is induced towards the well. Water is removed from storage, and the potentiometric level declines away from the pumping well, thereby creating a cone of depression around the well. This cone of depression continues to expand until the pumping can be balanced by (a) *an increase in recharge* to the system, induced by the lowering of the potentiometric level in the aquifer; (b) *a decrease in the discharge* from the system, resulting from the lowered potentiometric level in the system and decreased gradients in discharge areas; or (c) *a combination of increased recharge and decreased discharge* (Bredehoeft, 2002). The sum of increased recharge and decreased discharge is called capture (Lohman and others, 1972). If the well cannot capture enough water to balance pumping, water levels will continue to decline until pumping cannot continue at the initial rate. The capture of a pumping well does not depend on the initial recharge rate; rather, it depends on the change in recharge induced by the pumping well (Bredehoeft and others, 1982; Bredehoeft, 2002).

Ground-water pumping can capture streamflow in two ways for an initially gaining stream: (1) decreased discharge from the aquifer to the stream because of the lowered potentiometric gradient, and (2) induced infiltration from the stream to the aquifer because of a reversal in potentiometric gradient. In the second instance, the flow is from the stream toward the well, and the affected segment of the stream becomes a losing segment. The source of water to a pumping well changes with time from water released from storage to water captured because of decreased discharge or increased recharge, and this shift depends on the geometry of the system and aquifer properties (Bredehoeft, 2002). Appendix 1 offers an analysis of the various ways that the interaction between a pumping well and a stream have been quantified.

Purpose and Scope

The purpose of this report is to document the ground-water-withdrawal component of the Michigan water-withdrawal screening tool. In practice, the impact of wells on streams may not be limited to the ¼-mi buffer and 150 ft cutoff depth used in the original legislation so the ground-water component of the statewide assessment tool is designed to estimate streamflow depletion resulting from pumping a well without imposing arbitrary spatial constraints. The final screening tool also is designed to evaluate intermittent pumping and to account for the dynamics of stream-aquifer interaction so that ground-water withdrawals are not considered to be immediate from the stream at the pumping rate. Finally, the screening tool was designed to estimate the depletion from neighboring streams, not just from the stream closest to the proposed well.

In this report, the methods used to evaluate the impact of a new or increased ground-water withdrawal upon streamflow are described. Types of data required for the evaluation and the sources of data are provided. The distribution of streamflow depletion between neighboring streams is discussed in detail because the method used for this distribution was developed in this project. The screening tool was tested by comparison of results from it to streamflow depletion estimates generated with a numerical ground-water-flow model of Kalamazoo County, Mich. (Luukkonen and others, 2004), and these results are presented and discussed.

Study Approach

The ground-water component of the water-withdrawal screening tool was designed to account for the removal of water from storage and the resulting delay in the impact of new or increased pumping on streamflow. As a conservative approach, the only sources of water to the well in the screening tool are storage and streamflow depletion. For the screening tool, recharge to the aquifer is assumed to be unaffected by the addition of a high-capacity well. Several other potential sources of water to the well are omitted in this approach, including decreased loss of ground water to vegetation capable of using shallow ground water, and changes in water exchange between adjacent aquifers through semiconfining layers. The pumping well also is assumed to not significantly affect the water level in the stream. Because stream elevation and recharge are assumed to be unaffected by the additional pumping, natural seasonal variation in the system (including variations in stream elevation and recharge) does not influence the estimation of streamflow depletion.

As stated by Bredehoeft (2002) and described in appendix 1, the only way to assess capture by a pumping well is by using either analytical or numerical approaches to model the system. In general, analytical models are applicable for simple geometries and uniform aquifer properties, whereas numerical models allow for more complicated systems. For simple systems, both approaches yield similar estimates. For more complicated systems, analytical solutions may not capture the complexity of the system. Numerical models can describe a more complicated system, but these models require more extensive site-specific data and analysis. The goal of this project was to devise a procedure applicable for statewide screening; therefore, an analytical model was selected to estimate streamflow depletion by a pumping well. Use of an analytical model yields a screening tool that is sufficiently accurate but requires minimal input data and user training.

Ground-Water-Withdrawal Component of Screening Tool

Upon review of the literature related to modeling streamflow depletion by pumping wells, the analytical model selected for the ground-water component of the water-withdrawal screening tool is an equation derived by Hunt (1999). This analytical model describes streamflow depletion by a pumping well for a partially penetrating stream in an infinite aquifer with streambed resistance between the stream and the aquifer. This analytical model is appropriate for Michigan streams, which typically do not fully penetrate the aquifers used for water supply, and it is sufficiently simple for statewide screening. This analytical model was implemented in a Fortran computer code (Reeves, 2008). In the final implementation of the screening tool, an Internet-accessible version of the analytical model was required. The essential elements of the analytical model were programmed in VBScript (Microsoft Corporation, 2007) for implementation in the Internet version. This report includes verification that the VBScript version of the analytical model yields solutions similar to those from the Fortran version documented by Reeves (2008).

To illustrate the aquifer properties required by the analytical model, the form of the model is a useful summary. Hunt (1999) derives the analytical model as

$$Q_s = Q_w \left[\operatorname{erfc}\left(\sqrt{\frac{Sd^2}{4Tt}} \right) - \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda d}{2T} \right) \operatorname{erfc}\left(\sqrt{\frac{\lambda^2 t}{4ST}} + \sqrt{\frac{Sd^2}{4Tt}} \right) \right], \tag{1}$$

where

- Q_s is the rate of streamflow depletion (length cubed per unit time),
- Q_w is the pumping rate (length cubed per unit time),
- erfc() is the complementary error function (dimensionless),
- exp() is the exponential function (dimensionless),
- d is the distance from the well to the stream (length),
- S is the storage coefficient, or storativity, of the aquifer (dimensionless),
- T is the transmissivity of the aquifer (length squared per unit time),
- t is the time from the start of pumping, and
- λ is the streambed conductance term (length per unit time).

The major assumptions used to derive equation 1 (Hunt, 1999) are the following:

- Horizontal flow dominates any potential vertical flow; the Dupuit assumption is valid.
- The aquifer is homogeneous and isotropic and has constant saturated thickness.
- The aquifer is either confined or, if unconfined, change in hydraulic head in the aquifer is small compared to the saturated thickness.
- The stream is straight, infinitely long, and remains in hydraulic connection with the aquifer.
- The pumping does not change the stage of the stream.
- Recharge to the system is unchanged by pumping.
- The streambed may offer resistance to ground-water flow.
- There is no streambank storage.
- The pumping rate is constant.
- The aquifer extends to infinity.

Examination of equation 1 reveals that streamflow depletion depends on aquifer and streambed properties, the distance from the well to the stream, and time. In this model, streamflow depletion is described by a Darcy expression describing the flux between the stream and the aquifer (Hunt, 1999). The aquifer is assumed to remain in hydraulic contact with the stream, which means that the pumping well does not cause the hydraulic head in the aquifer to be lower than the streambed. See appendix 1 for more discussion of this assumption. To examine the sensitivity of streamflow depletion results on variations of input parameters, see Hunt (1999) and Reeves (2008).

The aquifer is assumed to be infinite, and, therefore, no additional data regarding the aquifer geometry are required by the model beyond the distance between the well and the stream. The remaining model input includes transmissivity, streambed conductance, storage coefficient, pumping rate, and time desired for the evaluation. As described in Reeves (2008), the analytical model was implemented in the computer code STRMDEPL08, which was used for development of the screening tool, with the option to simulate time-varying pumping rates.

Input of Constant and Time-Varying Pumping Rates

The impact of time-varying pumping is estimated in the screening tool because removal of water from storage may reduce the streamflow depletion. The streamflow depletion caused by time-varying pumping may be much lower than the pumping rate, and the estimated depletion caused by time-varying pumping often continues in time even while the pump is off. For analysis of streamflow depletion resulting from a constant pumping rate, the user must input the pumping rate. The duration of pumping in the screening tool is set to 1,825 days (5 years). For time-varying pumping, the user must not only provide the pumping rate but also a pumping schedule. Appendix 1 provides more discussion regarding the affect of time-varying pumping rates.

The interface to the screening tool prompts the user for more information if the user indicates a ground-water withdrawal with time-varying pumping. The user must enter the months when the well will be pumped, the well capacity, the days per week that the well will be pumped during those months, and the hours per day pumped. If the hours pumped per day are less than 24, the well capacity is prorated to yield a daily pumping rate. The days per week and months of pumping are then evaluated to determine the number of times that the pumping rate is changed. A superposition in time technique is used to account for time-varying pumping in the screening tool. Assuming that only streamflow depletion caused by a new or increased use is of interest, the equation for superposition used to evaluate time-varying pumping may be written as

$$Q_s(t_i) = \sum_{k=1}^{i} \Delta Q_k(t_k) R(\Delta t_k) \,, \tag{2}$$

where

$Q_s(t_i)$ is the streamflow depletion at time interval i (length cubed per unit time),
$\Delta Q_k(t_k)$ is the change in pumping rate during the interval k (length cubed per unit time),
$R(\Delta t_k)$ is the ratio of streamflow depletion to pumping rate given by equation 1 for time interval k (length cubed per unit time),
t_i is the length of time from the beginning of the pumping analysis to the time of interest,
Δt_k is $t_i - t_k$, the difference in time between the time of interest and the time when the pumping rate changed for interval k,
i is the number of times when the pumping rate changes (dimensionless), and
k is the time interval number (dimensionless).

Streamflow depletion is estimated for every time when the pumping rate changes and at the end of the 5-year evaluation period. The maximum streamflow depletion from each of these estimations is identified in the screening tool and used to evaluate the potential impact of the proposed pumping.

Aquifer Properties Required for the Water-Withdrawal Screening Tool

The analytical model used for the water-withdrawal screening tool, equation 1, requires aquifer transmissivity, streambed conductance, and aquifer storage coefficient. One of the assumptions is that the aquifer is homogeneous. Aquifers in Michigan, however, are typically heterogeneous. For the screening-level evaluation, an estimated transmissivity and storage coefficient were assigned to watersheds and used in the screening tool. A safety factor was assigned in the screening tool to allow for more site-specific evaluation of withdrawals that may lead to adverse environmental impact. The procedures used to assign aquifer properties to watersheds for the water-withdrawal screening tool are presented in this section.

For the statewide water-withdrawal screening tool, the most consistent source of aquifer properties was assembled recently into the Michigan Ground Water Inventory and Map (GWIM) database (Michigan Department of Environmental Quality, 2005). The GWIM database includes estimates for aquifer transmissivity mapped to a 1-km by 1-km (3,281 ft by 3,281 ft) grid across the State for glacial deposits and bedrock aquifers. Constant values for aquifer storage coefficient were assumed in the GWIM analysis for illustration of potential well-to-well impacts. These values were different for the glacial deposits and bedrock aquifers, but the values for both types were indicative of leaky (semiconfined) systems.

The range of storage coefficients observed in aquifer tests in Michigan is discussed later in this report. The GWIM database information was used to assign transmissivity, streambed conductance, and storage coefficient in the screening tool.

Definition of Valley Segments

The surface-water spatial framework used for the ground-water component of the water-withdrawal screening tool was built on the classification of Michigan stream arcs into ecological valley segments (Seelbach and others, 2006; Brenden and others, 2008; Zorn and others, 2009). Each valley segment is a contiguous length of stream with relatively homogeneous hydraulic, hydrologic, and ecologic characteristics. The catchment area, which is the surface watershed drainage area, for each valley segment was defined by combining the surface catchments of the approximately 30,000 individual stream arcs in the 1:100,000-scale National Hydrography Dataset (NHD) as processed in the Great Lakes Regional Aquatic Gap project (Morrison and others, 2003; Brenden and others, 2006). The final framework consists of approximately 10,000 valley segments. The reduction in streamflow caused by a ground-water withdrawal is assigned to the downstream point of the valley-segment catchment. To apply the water-withdrawal screening tool, aquifer properties were required for each unique valley segment.

Assignment of Aquifer Properties for Glacial Deposits to Valley Segments

Three aquifer properties are required by the analytical model: transmissivity, streambed conductance, and storage coefficient. Values for these properties were estimated from information in the GWIM database (Michigan Department of Environmental Quality, 2005). In this database, transmissivity of glacial deposits is mapped to a grid for the entire State of Michigan. The median transmissivity for the grid cells within each valley segment catchment is assigned to the valley segment and used in the screening model. The median was selected as the representative statistic instead of the arithmetic mean because the median is less influenced by extremely low or high transmissivity estimates in the database and therefore may be the more reasonable statistic for screening-level estimation.

The streambed conductance used in equation 1 may be written as

$$\lambda = \frac{(K_v w)}{b}, \qquad (3)$$

where

K_v is the vertical hydraulic conductivity of the aquifer (length per unit time),

w is the stream width (length), and

b is the distance from the bottom of the stream to the top of the well screen or open interval of a bedrock well (length).

The distance from the bottom of the stream to the top of the well screen or open interval, b, is provided as the well depth by the user. For the statewide screening, the stream width was estimated by use of a regression equation developed to relate stream width to drainage area of a stream segment (T.G. Zorn, Michigan Department of Natural Resources, written commun., 2007):

$$w = 3.28 * (10 \,\hat{}\, ((0.522358 * \log(da * 1.6093 \,\hat{}\, 2)) - 0.18786)) \quad , \qquad (4)$$

where

da is the drainage area of the catchment (square miles) and

w is width (feet).

An estimate of the vertical hydraulic conductivity of the aquifer was computed by dividing the median transmissivity by the average thickness of aquifer material for each valley-segment catchment. This thickness was estimated by interpolating the thickness used for the wells in the GWIM transmissivity-estimation procedure to a 3,281 ft by 3,281 ft grid over the State and then computing the mean estimated thickness for the grid cells within each valley-segment catchment. To avoid dividing by zero in areas where glacial deposits are thin, a minimum value of 5 ft was assigned.

Equation 2 allows the streambed conductance used in the screening tool to vary with the depth to the top of the well screen entered by the user. A factor of 1/10 is included in the estimated streambed conductance to account for the anticipated anisotropy of aquifers in Michigan. This factor is reasonable for aquifers without clay units and probably underestimates the anisotropy in areas where clay layers are present (Todd and Mays, 2005). Anisotropy in hydraulic conductivity describes the tendency for the aquifer material to have less resistance to flow in the horizontal direction than the vertical direction primarily because of layering of the system: underestimation of this factor is conservative in the estimate of streamflow depletion by a pumping well. Because the user may request site-specific review of a proposed withdrawal if the screening tool identifies it as having greater potential for causing adverse environmental impact, this conservative factor was appropriate. The final expression for streambed conductance used in the screening tool is

$$\lambda = \frac{\left((T / B')w / 10\right)}{b}, \qquad (5)$$

where

B' is the estimated mean thickness of glacial deposits for the valley-segment catchment (length) and

b is the input value of depth to the top of the well screen or open interval of the well (length).

The final aquifer property is storage coefficient. In the analysis for the GWIM, constant values for storage coefficient were used: 0.0016 for glacial deposits and 0.0004 for bedrock aquifers. These values were determined by use of the geometric means of reported storage coefficients from aquifer tests reviewed by the State. For the screening tool, the value for the glacial deposits was believed to be too small, resulting in overprediction of the streamflow depletion from wells in unconfined or leaky aquifers. The storage coefficients reported for aquifer tests in glacial deposits vary over four orders of magnitude and do not correlate well with location in the State, surficial geology, or depth. Relation of storage coefficient with depth is illustrated in figure 1. On the statewide scale, it has not been possible to reliably identify areas of Michigan dominated by confined, leaky, or unconfined conditions. Use of the geometric mean, or a smaller value typical of a confined aquifer, may lead to a potentially contradictory situation where the assumption is made in the screening tool that the aquifer behaves as confined but also in good hydraulic contact with headwater streams. Conversely, assuming that an unconfined specific yield represents statewide conditions is not conservative, especially for time-varying pumping estimates. To give a conservative estimate that is consistent with the observed uncertainty in the estimated storage coefficients across the state, a constant value of 0.01, which is representative of a leaky aquifer, was used in the screening tool.

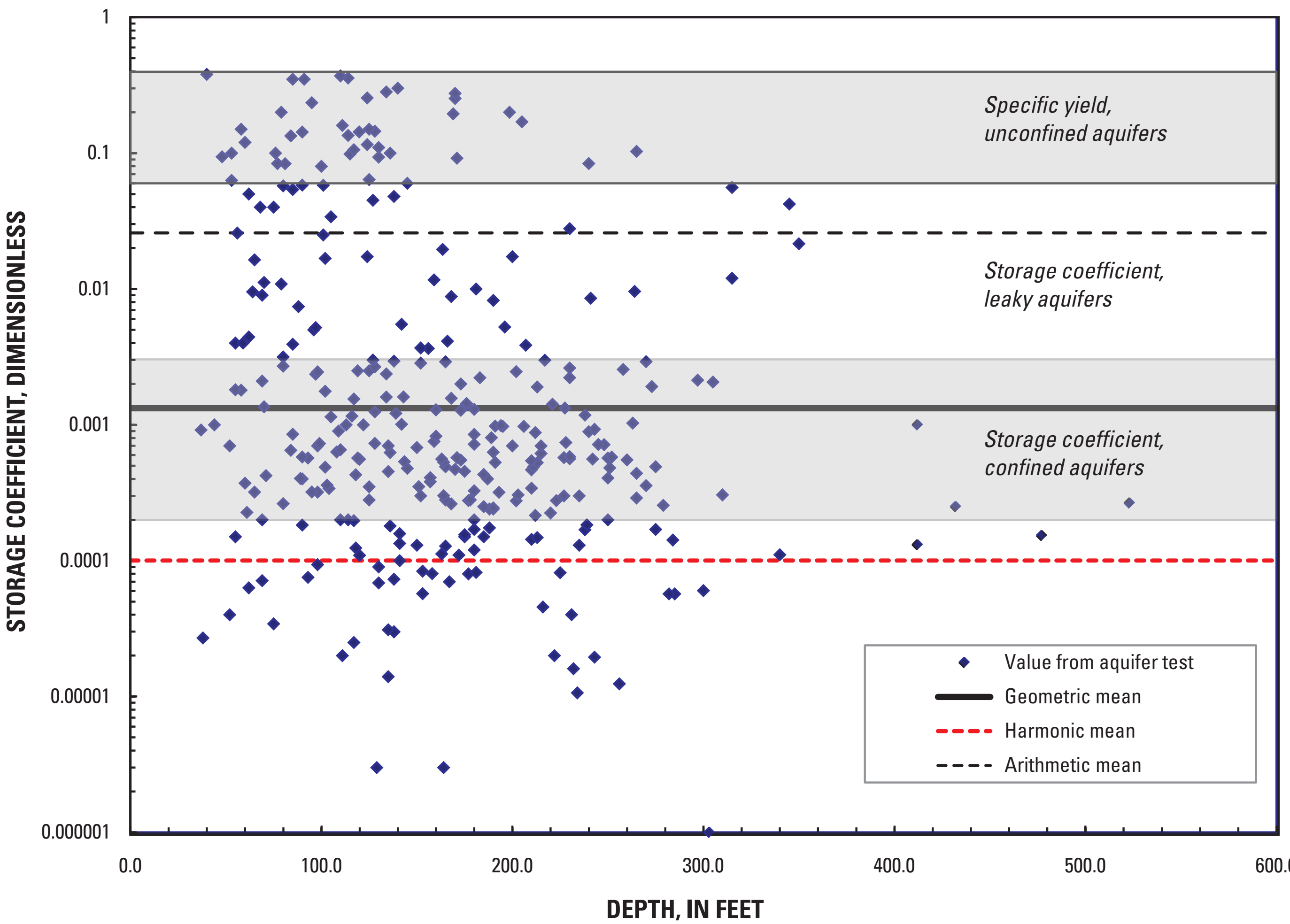
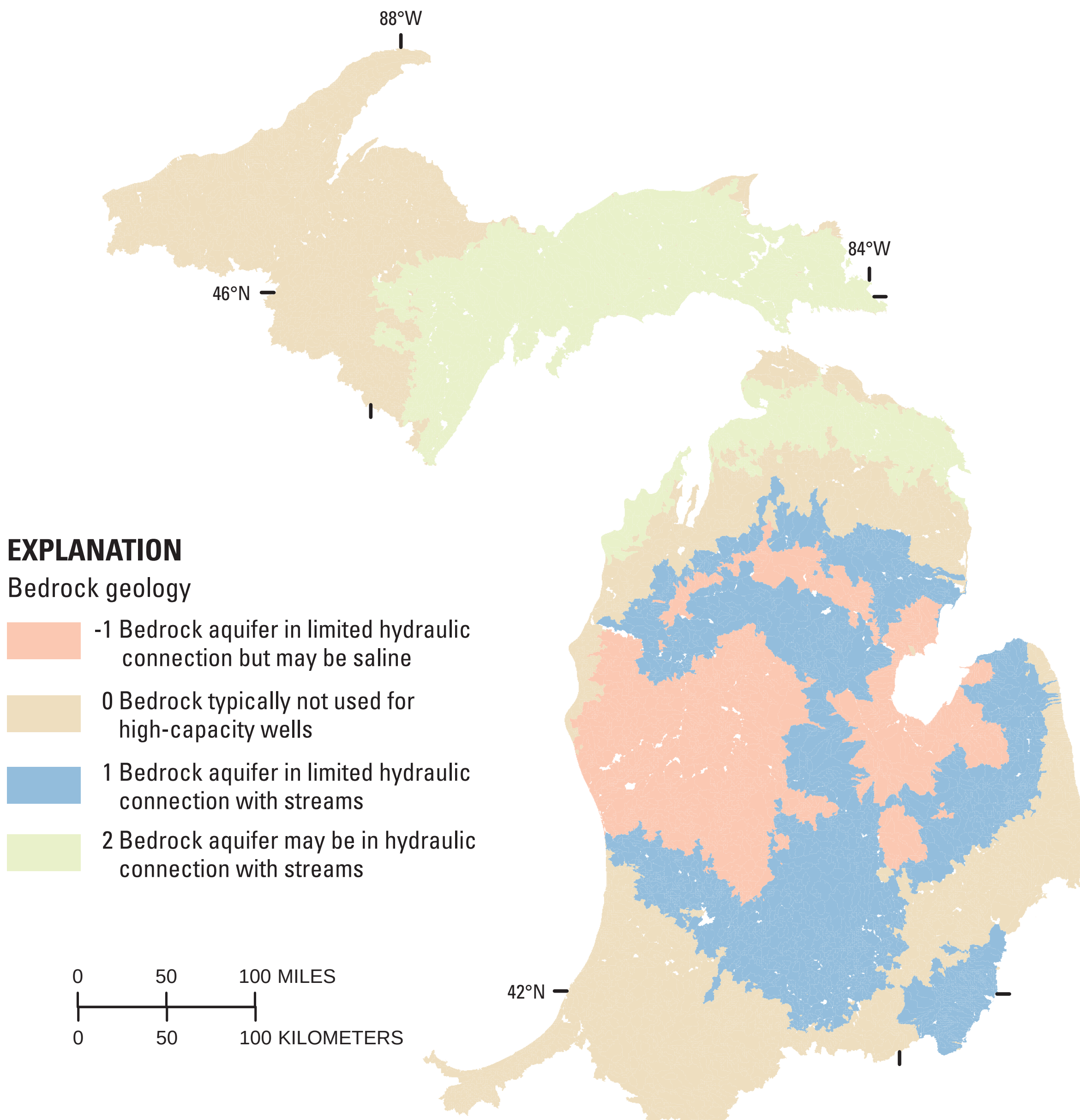


Figure 1. Reported aquifer storage coefficients for wells completed in glacial deposits from aquifer tests reviewed by the State of Michigan as a function of depth; arithmetic, geometric, and harmonic means also are shown. Shaded zones show typical ranges of specific yield and storage coefficient (for a 100 foot aquifer) for unconsolidated materials (Domenico and Schwartz, 1990).

Assignment of Bedrock Aquifer Properties to Valley Segments

Bedrock aquifers are used in parts of Michigan, and in some areas of the State these bedrock aquifers are separated from overlying streams by thick glacial deposits containing layers of material with low hydraulic conductivity, such as silt or clay. In these areas, the hydraulic connection between these aquifers and nearby streams is limited. In other areas, there may be a greater hydraulic connection between the bedrock aquifer and overlying streams. Saline water may be present in some areas of the major bedrock aquifers, and it may occur at depth under a freshwater zone or through the entire thickness of the bedrock aquifer. Finally, in some areas of the State, bedrock aquifers are not suitable for high-capacity wells. To account for these different potential conditions in the screening tool, the bedrock aquifers were grouped into four categories (fig. 2). The categories and response given by the water-withdrawal screening tool are summarized in table 1.



Bedrock geology from Michigan Department of Environmental Quality, 1987

Figure 2. Four bedrock categories used in the water-withdrawal screening tool for Michigan.

Table 1. Bedrock categories and response by water-withdrawal screening tool to proposed bedrock well in each category.

Bedrock category	Description of bedrock hydraulic conditions	Response from water-withdrawal screening tool
-1	Bedrock aquifers typically in only limited hydraulic connection with streams but in areas where ground water in the bedrock aquifer is potentially saline based on a regional assessment (Westjohn and Weaver, 1996). Note that in some areas, saline water may occur at depth below a freshwater zone, and in other areas, saline water may be present throughout the entire bedrock thickness.	The proposed well passes the screen and the user is informed to register the use as required by statues. Because in some areas identified as saline (Westjohn and Weaver, 1996) bedrock wells may produce potable water and saline water becomes an issue only for deeper bedrock wells, this flag is not used in the current version (January 2008) of the screening tool. The information is retained in the underlying database in case this information is desired in future versions. The user is warned in all uses of the screening tool that the tool is not intended as a design tool and that the evaluation does not guarantee ground-water quantity or quality.
0	Bedrock typically not used for high-capacity wells because the dominant bedrock unit in the area is not a productive aquifer. For example, this category is used for areas in the state underlain by the Coldwater Shale.	The user is informed through a pop-up message that bedrock aquifers in this area are generally not used for high-capacity wells. The screening tool uses aquifer properties from the glacial deposits to evaluate the potential streamflow depletion for the proposed well.
1	Bedrock aquifers typically in only limited hydraulic connection with streams, especially smaller streams.	The proposed well passes the screen, and the user is informed to register the use as required by statues.
2	Bedrock aquifer may have hydraulic connection with streams.	The proposed withdrawal is evaluated by use of bedrock properties from the Ground-Water Inventory and Map database that were processed in the same way as the properties for the glacial deposits. The streambed conductance between the bedrock aquifer and the stream is estimated by use of the properties of the glacial deposits overlying the bedrock. The assigned storage coefficient is 0.0004, as used in the Ground-Water Inventory and Map.

Definition of Great Lake Shoreline Catchments

Many small valley-segment catchments were defined adjacent to one of the Great Lakes. If the valley segment in a catchment adjacent to a Great Lake did not contain a stream or was smaller than approximately 3 to 6 mi^2, then the valley-segment catchment was designated as a shoreline catchment. No limitation on depletion was set from these shoreline catchments because pumping was assumed to come from the lake and not adversely impact a stream. Entities proposing withdrawals greater than 2 Mgal/d, however, are required to obtain a water-withdrawal permit (Public Act 180 of 2008 (2008 PA 180), Michigan State Legislature, 2008b), and the potential ecological impact of such withdrawals may be assessed in the permitting process.

Distribution of Streamflow Depletion Among Valley Segments in Neighboring Catchments

Unlike direct surface-water withdrawal, ground-water withdrawals are thought to potentially affect valley segments in neighboring catchments. The analytical solution, however, estimates streamflow depletion only between the well and a single stream. Nine different methods to apportion streamflow depletion among neighboring valley segments were evaluated. Details regarding this evalution are presented in appendix 2. The simplest approach is to estimate streamflow depletion only for the valley segment draining the catchment containing the well. This simple approach, however, performed the worst compared to the results from a numerical ground-water-flow model. On the basis of the analysis, an inverse distance method was selected for the screening tool because (1) it produces a reasonable overall pattern of streamflow depletion compared to a numerical ground-water-flow model, (2) it is the most straightforward to implement in the Internet-based screening tool, and (3) it has some theoretical basis in steady-state analysis (Wilson, 1993). The weighting used for this distribution method may be written as

$$f_i = \frac{\frac{1}{d_i}}{\sum_{j=1,n} \frac{1}{d_j}}, \tag{6}$$

where

f_i is the fraction of the captured water attributed to valley segment i,

n is the number of adjacent valley-segment catchments, and

d_i is the distance from the proposed well to the closest point on the valley segment within catchment *i*.

Demonstration of Analytical Model and Distribution Approach

The ground-water-flow model for the area around Kalamazoo County, Mich. (Luukkonen and others, 2004) was used to test the nine distribution methods discussed in appendix 2 and to demonstrate the performance of the analytical model used in the screening tool. The ground-water-flow model is a finite-difference (MODFLOW) simulation model with 6 layers, 154 rows, and 162 columns. The smallest grid spacing in the model is 660 ft by 660 ft. Valley-segment catchments in the interior of the model that have this finest grid spacing were used in the methods testing. The model used for the test case includes approximately 90 existing wells, and streamflow depletion caused by the addition of a new well to different parts of the model is examined. To illustrate the applicability of the analytical model and distribution approach to field problems, a transient simulation with seasonally varying recharge and pumping rates was used as the test case. Luukkonen and others (2004) presented the results for a 9-year transient simulation; but, in this work, the length of the simulation was reduced to 5 years to reduce computer run time (fig. 3). The simulation illustrates seasonal pumping and recharge. This simulation is used in the demonstration to illustrate that the analytical model given by equation 1 is not affected by time-varying areal recharge as long as the areal recharge is independent of the imposed pumping. Because areal recharge in the numerical model is specified and does not depend on the pumping imposed on the system, the numerical model is consistent with the assumptions made in the analytical model. For many cases in Michigan, pumping will not induce increased recharge, and this assumption is valid at least on a screening level.

A method to illustrate streamflow capture by pumping wells (Leake and Reeves, 2008) was used to examine the spatial distribution of streamflow capture from the valley segments. In this method, hypothetical wells are added to the MODFLOW model sequentially on a grid of cells (fig. 4).

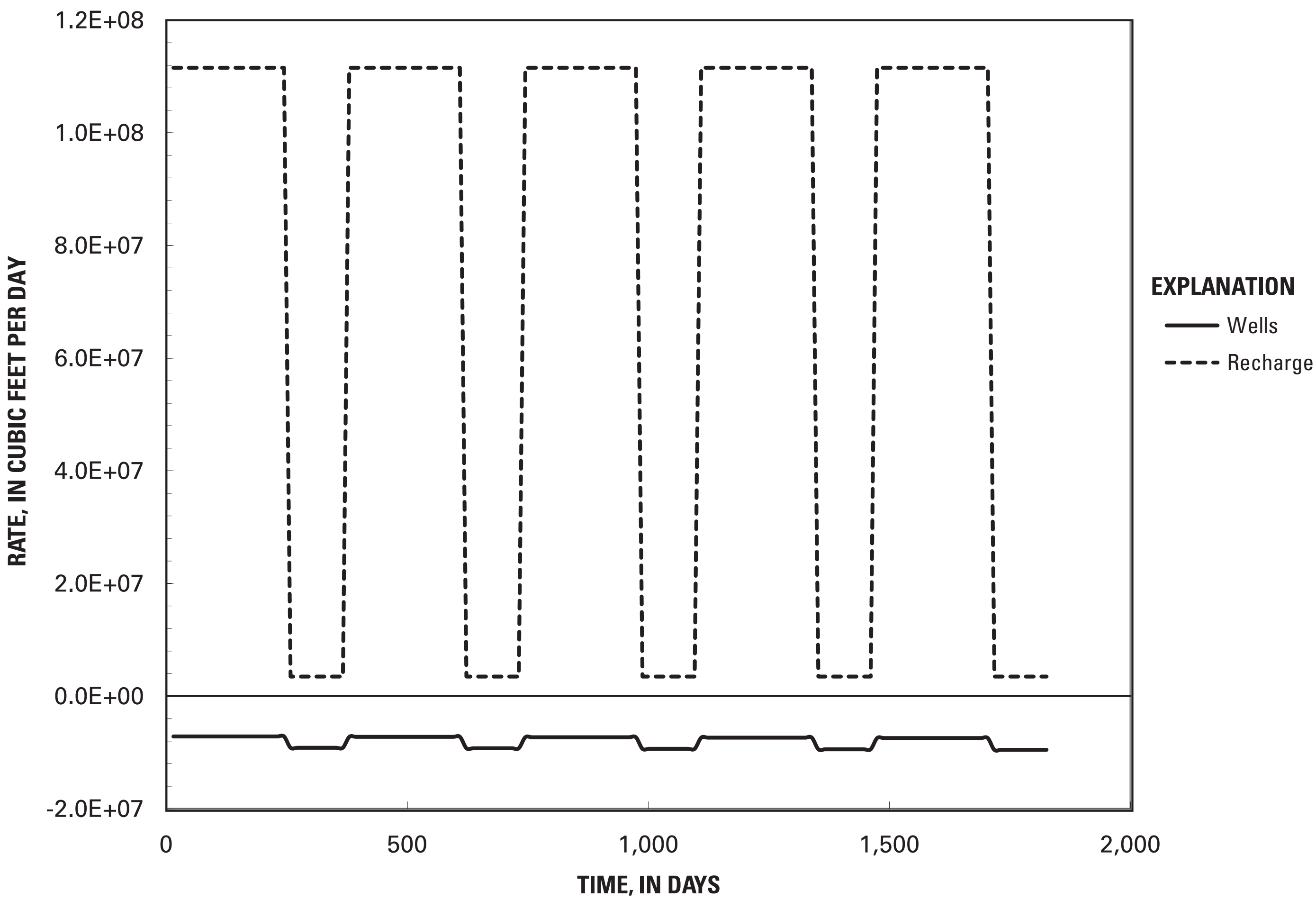


Figure 3. Recharge and pumping rates used in the base simulations with the Kalamazoo regional ground-water-flow model (Luukkonen and others, 2004).

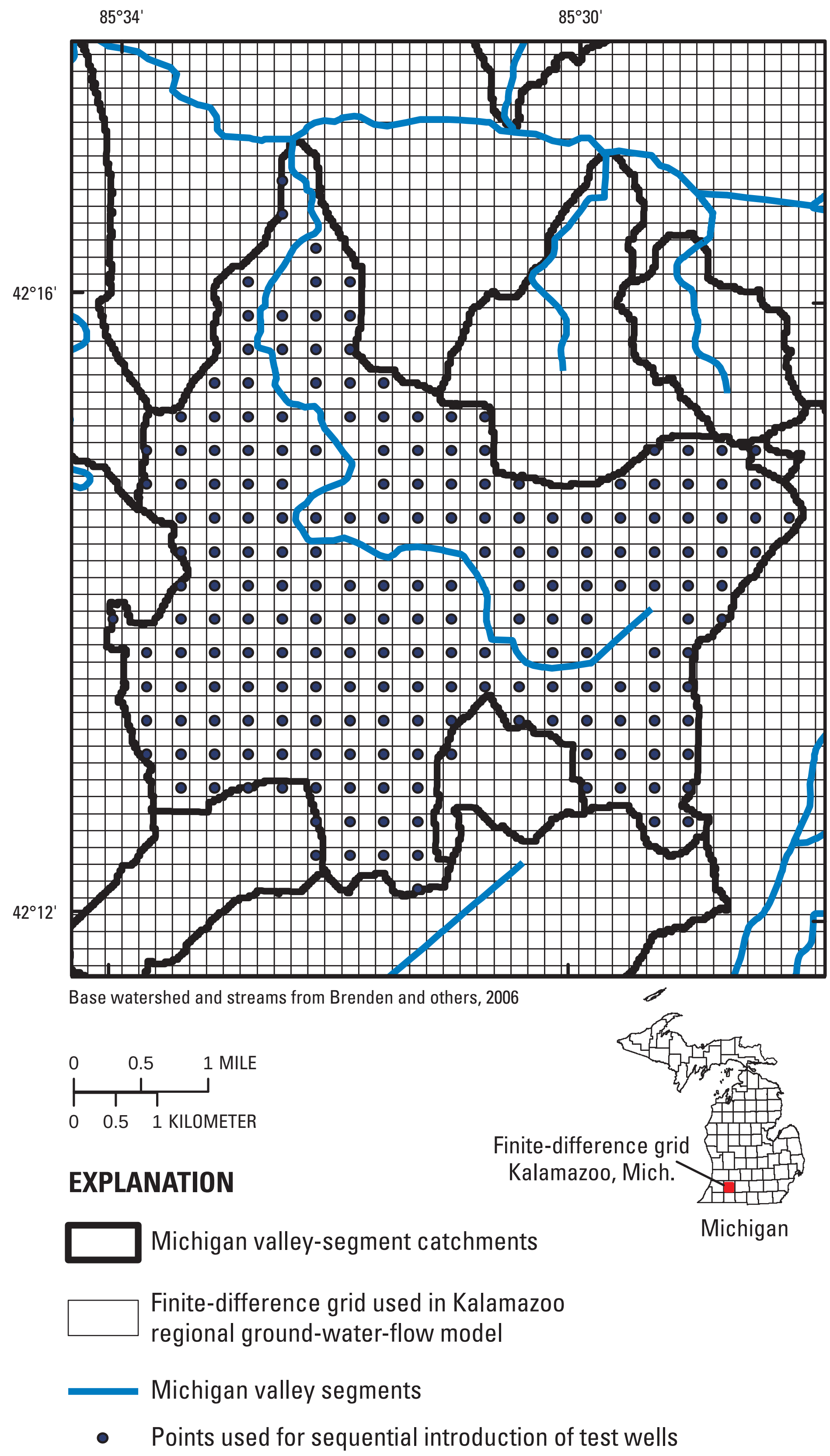


Figure 4. A grid of points used to compare the analytical model and different distribution methods to MODFLOW results from the Kalamazoo regional ground-water-flow model (Luukkonen and others, 2004).

One well is added to a specified cell, and the new simulation is computed. The results from this new simulation are subtracted from base-model results to determine the capture and change in storage caused by the new well. The process is repeated with one new well at a time, generating a grid of results that may be mapped. The fluxes to individual river cells representing the valley segments from the statewide data framework were computed. These fluxes were recorded by use of a river observation file (Hill and others, 2000) to designate the finite-difference cells assigned as river cells to the appropriate valley segments. The river flux output from the system with the new well for each designated valley segment was subtracted from the valley-segment flux computed with the original model to yield the streamflow depletion due to the new well as simulated with the MODFLOW model. Values for streamflow depletion as a percentage of pumping rate for the grid of wells shown in figure 4, which were placed in layer 3 of the model, are shown in figure 5. The two methods, MODFLOW and the analytical model, produce similar results for wells introduced into the test valley-segment catchment. The maximum depletion for wells introduced near the valley segment within the catchment is between 70 and 80 percent, and the minimum depletion near the boundary of the catchment is less than 10 percent (See appendix 2 for more detailed discussion of the methods to distribute streamflow depletion among neighboring valley segments).

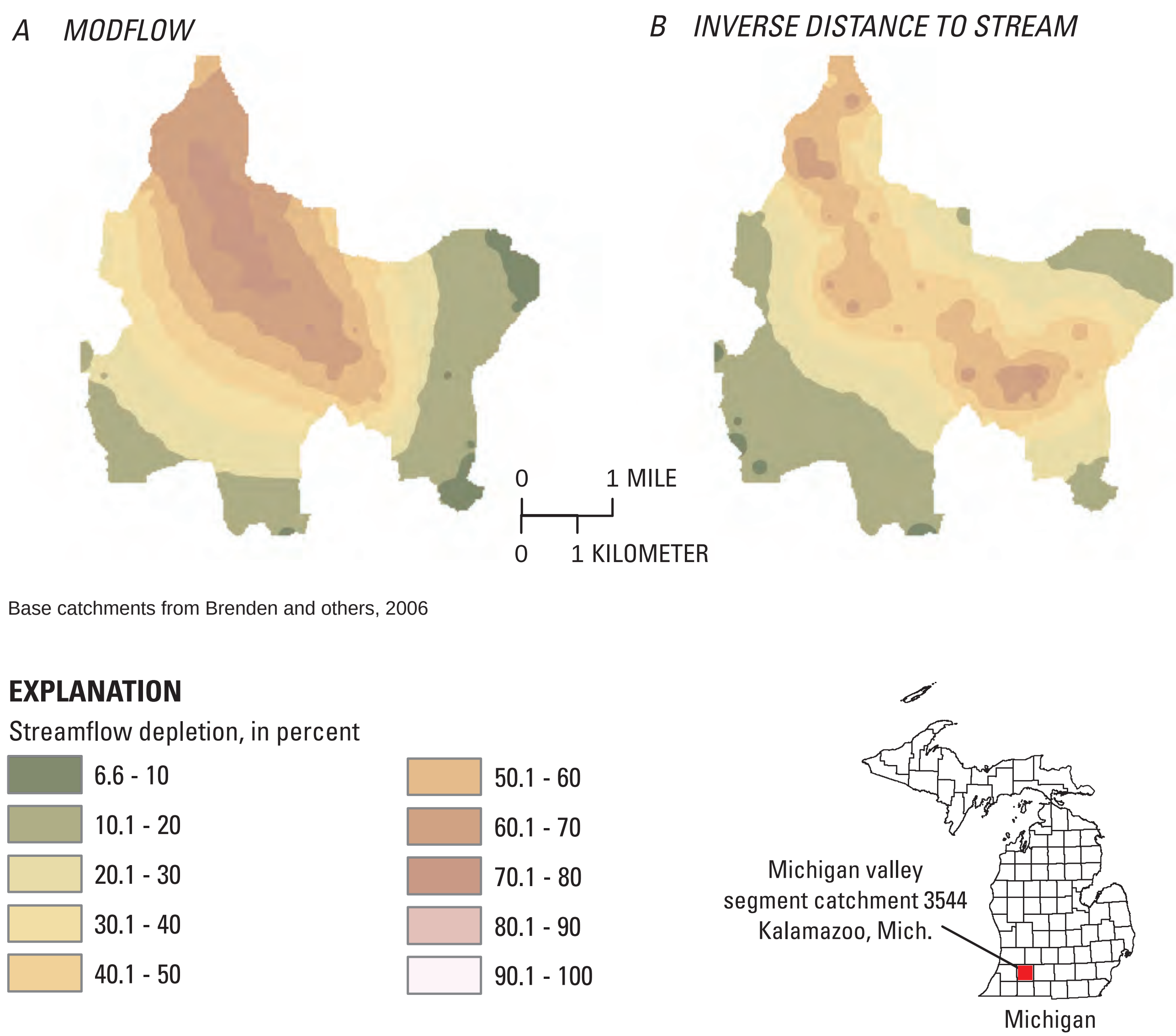


Figure 5. Estimated streamflow depletion from valley segment 3544 as a percentage of pumping rate after 5 years of pumping. *A*, results from a sequential introduction of test wells in the MODFLOW ground-water-flow model for Kalamazoo County, Mich. *B*, results from analytical model with inverse distance to stream distribution of streamflow depletion.

Limitations of Testing

The MODFLOW simulation model for the Kalamazoo area provides a convenient way to test the analytical model and distribution methods. The ground-water-flow model, however, is a regional simplification of the flow system, and neither the MODFLOW model nor the analytical model may accurately estimate the true impact of a specific well on a specific stream in the area. Site-specific investigation would be required for such an estimate. The MODFLOW model resolution of the stream network and well distribution also affects the estimates. The smallest grid size in the ground-water-flow model is 660 ft by 660 ft, and this becomes the shortest distance between the well and the stream that can be tested with the MODFLOW model. If a test point is placed in the same cell as a valley segment, the effective distance between the well and the stream is zero in the MODFLOW model. For the test grid (fig. 4), no wells were placed in valley-segment cells. The distances used for the analytical model are from geoprocessing of the data-framework files. These distances are more accurate than those used in the MODFLOW model, and some mismatch between MODFLOW results and the analytical estimates is expected because of these distance differences. In addition, the aquifer characteristics used in the MODFLOW model are different from those used in the analytical model. The transmissivity, storage coefficient, and streamflow-conductance values used in the analytical model in the test were estimated from the statewide databases, as described earlier in this report. The values used in the MODFLOW model, however, were the calibrated values from Luukkonen and others (2004). Different input values were used to more fully test the approach for the screening tool described previously. The reasonable match between the MODFLOW results and the analytical-model results supports the use of the analytical model, the use of the estimated aquifer properties derived from the GWIM database, and the use of the inverse-distance weighting scheme to distribute streamflow depletion among neighboring valley-segment catchments.

The aquifer and surface-water network in Kalamazoo County is not necessarily representative of conditions across all of Michigan. In addition to this quantitative test, a series of qualitative ad hoc tests were performed by applying the analytical model to locations of high-capacity wells in every county of the state. The ad hoc tests relied on the experience of the testing team to assess whether the results appeared to be reasonable, and no major problems were identified through this testing.

Summary of the Ground-Water Component of the Water-Withdrawal Screening Tool

The water-withdrawal screening tool was designed to be accessed through the Internet. This access required the integration of several technologies. The screening tool essentially implements the analytical model and inverse-distance weighting distribution method described in the previous sections but with different computer software than used in the testing and development. A brief list of steps may help illustrate the ground-water component of the screening tool. The overarching technology is an ArcIMS Web site (Environmental Systems Research Institute, Inc. (ESRI), 2004) that provides a map interface to the screening tool for the user. The following is the sequence of steps for a typical screening-tool session:

1. When the user enters the location for a new withdrawal, a server running ArcView with Avenue Scripts (for example, Razavi and Warwick, 1999) determines the valley segment containing the proposed well.

2. The user specifies whether the proposed well is in glacial deposits or bedrock. If bedrock, then the bedrock type for the valley-segment catchment is identified.

3. A GIS data file is accessed to gather the aquifer properties assigned to the valley-segment catchment and to determine whether the valley-segment catchment is identified as a Great Lake shoreline catchment.

4. The neighboring valley segments are identified.

5. The distances from the proposed well to the nearest valley segment in each of the valley-segment catchments are computed.

6. VBScripts are used to run the Hunt (1999) analytical model (equation 1) for each of the valley segments using the aquifer properties for the valley-segment catchment containing the well and the distances computed in step 5. If the user specifies time-varying pumping, then superposition (equation 2) is used to compute the maximum streamflow depletion during the 5-year evaluation period. For steady pumping, the solution is evaluated after 5 years of pumping.

7. VBScripts are used to distribute the streamflow depletion between the neighboring valley segments using inverse distance weighting (equation 6).

8. Additional scripts are used to collect this information, compare the results to streamflow estimates, and apply screening rules to provide feedback to the user.

Example Screening and Confirmation of Water-Withdrawal Screening-Tool Results

The tests of the analytical model presented in this report were generated by use of Python scripts and the Fortran-based STRMDEPL08 program (Reeves, 2008). The STRMDEPL08 program was used to evaluate the Hunt (1999) analytical model (equation 1). Examples were run in this manner as batch tests for the technical subcommittee of the GWCAC. Because the STRMDEPL08 program has been documented by Reeves (2008), it serves as a standard for comparison of the Internet-based water-withdrawal screening tool. In this final section, results from the water-withdrawal screening tool using the sequence of ArcIMS, VBScript, and Avenue scripts listed above are shown to match results from STRMDEPL08 with inverse-distance weighting applied to distribute withdrawal among neighboring valley segments.

For this demonstration, an example in the northern part of the Lower Peninsula of Michigan (fig. 6) was evaluated with the water-withdrawal screening tool. The latitude and

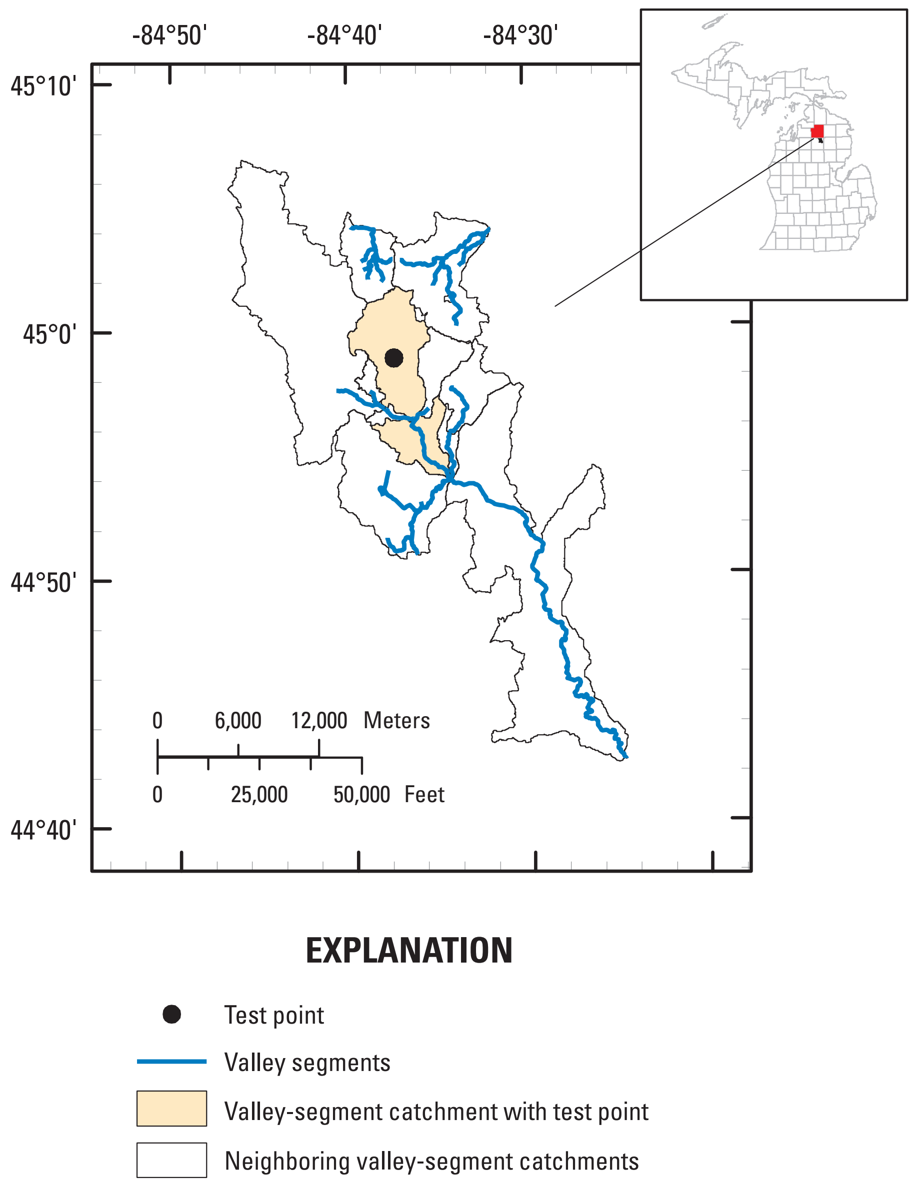


Figure 6. Example test point, valley-segment catchment containing the point, and neighboring valley-segment catchments.

longitude of the point were input to the Python scripts used for the screening-tool development. The point, the valley-segment catchment containing the point, the neighboring valley-segment catchments, and the neighboring valley segments identified by the Internet-based suite of programs and the Python scripts were identical. The percent removal from each of the valley segments and the total removal given a well at a depth of 80 ft and a continuous pumping rate of 70 gal/min generated by the STRMDEPL08 program (Reeves, 2008) and the water-withdrawal screening tool were nearly identical (table 2). The differences between the STRMDEPL08 and water-withdrawal screening tool may be attributed to slight differences in the estimated distances between the proposed well and valley segments, most likely caused by round-off in the latitudes and longitudes used to locate the point.

Table 2. Compilation of estimates for an example test point using the Michigan water-withdrawal screening tool and the set of batch programs used in screening-tool development and testing.

[The number of digits used does not signify precision of estimates but is reported to show the difference between the two sets of calculations]

Valley segment identification	Distance to example well, feet		Removal from valley segment, percent		Analytical removal, gallons per minute		Estimated removal from valley segment, gallons per minute	
	Screening tool	Batch	Screening tool	Batch	Screening tool	Batch	Screening tool	Batch
8	14,802	14,798.9	9.89	9.89	52.02	52.02	5.15	5.15
9	12,609.2	12,609.6	11.61	11.61	54.30	54.30	6.31	6.30
11	15,750.5	15,745.0	9.30	9.30	51.05	51.03	4.75	4.74
27	22,567.6	22,562.4	6.49	6.49	44.24	44.25	2.87	2.87
9741	27,565.2	27,561.4	5.31	5.31	39.52	39.49	2.10	2.10
10532	33,059.5	33,052.5	4.43	4.43	34.62	34.60	1.53	1.53
11967	14,846.3	14,844.0	9.86	9.86	51.98	51.97	5.13	5.13
12515	17,042.5	17,033.9	8.59	8.59	49.73	49.73	4.27	4.27
12573	11,959.5	11,960.4	12.24	12.24	54.98	54.98	6.73	6.73
12941	19,070.8	19,063.4	7.68	7.68	47.69	47.71	3.66	3.66
13925	10,028.9	10,030.6	14.60	14.59	57.01	57.00	8.32	8.32

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Appendix 1. Background and Literature Review on Streamflow Depletion Modeling

Streamflow depletion has been modeled with various analytical and numerical models. The conceptual model underlying each approach may be used to distinguish and classify the analytical and numerical models. Five conceptual models and extensions are discussed to provide an overview of the relevant literature on streamflow depletion by wells.

Fully Penetrating Stream With No Streambed Resistance

The first conceptual model discussed in this report was used to derive a solution by Theis (1941) that was later recast in the now more familiar form by Glover and Balmer (1954). This model is for a stream that fully penetrates the aquifer. There is no resistance to flow offered by the streambed. The domain is homogeneous and extends to infinity away from the stream. The stream is infinite, and the interaction between the pumped aquifer and the entire stream length is considered. There is no flow across the bottom of the aquifer. Flow is horizontal (Dupuit approximation) and, if the aquifer is unconfined, then drawdown in the aquifer is small compared to the saturated thickness such that the system may be modeled with constant transmissivity (fig. 1–1*A*). Glover (1974) presents a solution to the problem that provides an estimate of streamflow depletion for an arbitrary length of the stream.

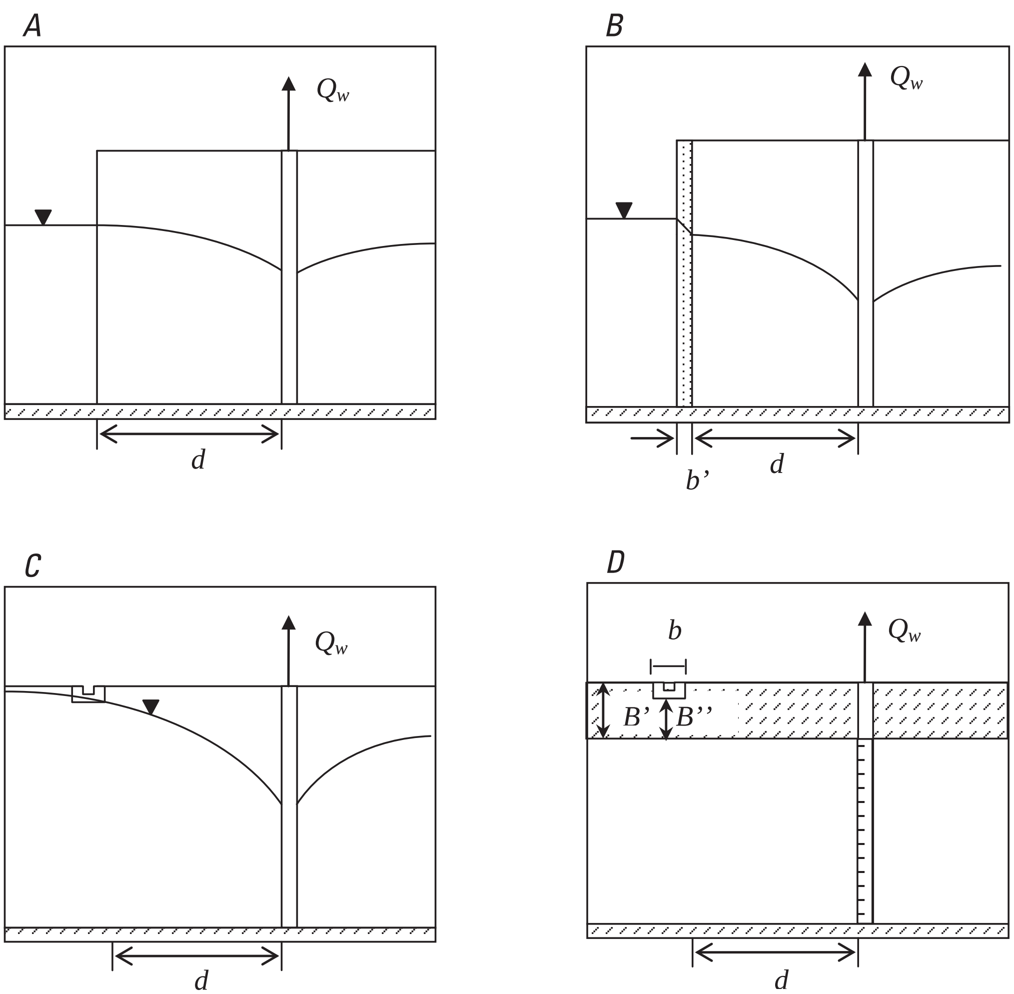

Figure 1–1. Alternate conceptual models for streamflow depletion by a pumping well. (*A*, Fully penetrating stream with no streambed resistance. *B*, Fully penetrating stream with streambed resistance. *C*, Partially penetrating stream with streambed resistance. *D*, Partially penetrating stream in semiconfining layer with pumping from underlying semiconfined aquifer. In the figure, d is the distance from the well to the stream, Q_w is the pumping rate from the well, b' is the thickness of the streambed, B' is the distance from the land surface to the top of the leaky aquifer, B'' is the distance from the bottom of the stream to the top of the leaky aquifer, and b is the width of the stream (Modified from Reeves, 2008)).

The Theis (1941) and Glover and Balmer (1954) solutions are transient but consider only a constant pumping rate. Jenkins (1968) and Wallace and others (1990) describe how to use superposition to extend the Glover and Balmer (1954) solution for intermittent or cyclic pumping rates. Jenkins (1968) introduces the concept of the streamflow depletion factor (*sdf*) that is used by several subsequent authors (for example, Burns, 1983). Jenkins (1968) focuses on the use of superposition to solve intermittent pumping problems and demonstrates that streamflow depletion continues for some time even after pumping has been stopped. Wallace and others (1990) examine the time required for the system to attain a dynamic steady state and the conditions under which a cycle-average pumping rate could be used in the estimation of streamflow depletion by cyclic pumping. Under certain conditions, discussed in the paper, the use of the cycle-average pumping rate to analyze streamflow depletion severely underestimates the peak depletion rates; therefore, an analysis with the true cyclic pumping rates is preferable. Barlow (2000) wrote a computer program to compute the Glover and Balmer (1954) solution for intermittent pumping, using the techniques described by Jenkins (1968).

In contrast to the transient solutions, Newsom and Wilson (1988) and Wilson (1993) present steady-state solutions to this problem. For all the solutions discussed for this conceptual model, the total streamflow depletion is the pumping rate because there are no other sources of water to allow the system to reach steady state other than capture from the stream. The Glover (1974) solution and the Newsom and Wilson (1988) or Wilson (1993) solutions can be used to estimate the amount of streamflow depletion in a prescribed length of the stream reach. As this length becomes large, the streamflow depletion from the specified stream reach approaches the pumping rate. The papers by Newsom and Wilson (1988) and Wilson (1993) illustrate the importance of regional ground-water flow on the solution. The analysis in the papers also distinguishes between streamflow capture by interception of ground water that would have been discharged from the aquifer as base flow and streamflow capture by induction of stream water into the aquifer. Wilson (1993) also provides analysis for a well between two streams with vertical recharge and for an aquifer with both a stream and a barrier boundary.

Distinguishing between capture from decreased base flow to the stream and induced infiltration from the stream may be important for water-quality analysis if the water-quality characteristics of the stream and the aquifer are different. The steady-state solutions may be used to analyze the infiltration rate of poor-quality surface water to a supply well or the discharge rate of contaminated ground water to a stream despite the installation of an extraction well. The critical pumping rate required to induce infiltration from the stream is shown to be a function of the angle between the ambient flow direction and the stream (Newsom and Wilson, 1988). If the ambient flow rate is perpendicular to the streambed, which is the typical situation, the critical flow rate is calculated as follows (Newsom and Wilson, 1988; Wilson, 1993):

$$Q_c = \pi \, d \, q_a , \qquad (1\text{–}1)$$

where

Q_c is the critical pumping rate, d is the distance between the well and the stream, and

q_a is the ambient flow rate of ground water to the stream per unit length of stream.

This last term is the specific discharge from the aquifer to the stream integrated by the thickness of the aquifer, and it has units of length squared per unit time (Newsom and Wilson, 1988). Newsom and Wilson (1988) present results that show that this critical pumping rate increases by approximately 10 percent at an approximate angle between the ambient flow and the streambed of 29 degrees. The critical pumping rate is increased for angles between 0 and approximately 55 degrees and decreases between 55 degrees and 90 degrees. For flow parallel to the streambed (90-degree angle between ambient flow and the streambed), the critical pumping rate is approximately 40 percent of the value given above.

Chen (2003) combines transient analysis and the questions posed by Newsom and Wilson (1988) and Wilson (1993) to present a transient investigation of induced infiltration from the stream and decreased base flow to the stream. In particular, Chen (2003) derives the critical time required to induce infiltration from the stream as

$$t_c = -\frac{d^2 S}{4T \ln(\pi q_a d / Q)} , \qquad (1\text{-}2)$$

where

t_c is the critical time when infiltration from the stream to the aquifer is induced,

T is the aquifer transmissivity (length squared per unit time),

S is the aquifer storage coefficient (dimensionless), and

Q is the pumping rate of the well (length cubed per unit time).

Chen (2003) also discusses the residual impact of pumping on streamflow after pumping has ceased. As noted by other transient analysis (for example, Jenkins, 1968; Wallace and others, 1990), streamflow depletion continues after pumping has stopped until, under this conceptual model, the total volume removed as streamflow depletion is the same as the volume of water removed from the aquifer by the intermittent pumping.

Fully Penetrating Stream With Streambed Resistance

Hantush (1965) presented the solution for the second conceptual model that includes streambed resistance as illustrated in figure 1–1*B*. The resistance in the streambed is described by a streambed leakance or retardation coefficient, $L = (Kb'/K')$, where K is the hydraulic conductivity of the aquifer, K' is the hydraulic conductivity of the streambed, and b' is the thickness of the streambed[1]. The streambed leakance term causes the interaction between the pumping well and the stream to be delayed. As discussed for the previous conceptual model, because there are no other sources of water for the well to capture, the streamflow depletion is the pumping rate at steady state. The Hantush (1965) solution is a transient solution for a constant pumping rate, and the superposition techniques described by Jenkins (1968) can be applied to this solution. Barlow (2000) includes the Hantush (1965) solution in the computer program cited above as an input option selected by the user.

Many solutions that consider streambed resistance also incorporate partial penetration of the streambed into the aquifer, and these solutions will be discussed in the next section. Three papers that evaluated analytical solutions and identified shortcomings with various conceptual models are now reviewed to emphasize the difference between the conceptual models and associated analytical solutions. Spaulding and Khaleel (1991) and Sophocleous and others (1995) analyzed the analytical solutions by Glover and Balmer (1954), Jacob (1950) (discussed in the next section), Hantush (1965), and Glover (1974) and provide results illustrating the importance of streambed resistance and partial penetration of the streambed into the aquifer. See figure 1–1*C* for an illustration of a partially penetrating streambed. Spaulding and Khaleel (1991) used a finite-element ground-water-flow model from the literature and Sophocleous and others (1995) used the finite-difference-based model MODFLOW (Harbaugh and others, 2000) to test the various analytical solutions for different conceptual models. Both papers conclude that streambed resistance and partial penetration of the streambed into the aquifer are important to the solution and that conceptual models that do not account for these factors may severely overestimate the streamflow depletion rate at a given time. Conrad and Beljin (1996) also used MODFLOW to investigate various assumptions inherent in the Wilson (1993) solution. These authors also investigated the impact of streambed resistance and partial penetration by the stream. In addition, they present tests exploring the impact of vertical anisotropy in the aquifer and of considering typical variations in stream levels on the simulation of the aquifer system. All of these papers show that partial penetration of the streambed into the aquifer and incorporation of streambed resistance are important features that should be included in the analysis of streamflow depletion.

Partially Penetrating Stream With Streambed Resistance

Hunt (1999) generalizes the problem more by considering a partially penetrating stream in a fully confined or unconfined aquifer. The rest of the assumptions used for the previous cases still hold: horizontal flow following the Dupuit approximation, small changes in saturated thickness for the unconfined case, and a homogeneous aquifer. In this case, the aquifer has infinite extent and the stream width and depth are small compared to the aquifer thickness, such that the stream may be modeled as a line (zero width). Hunt (1999) includes the resistance through a streambed using Darcy's Law, $Q = \lambda\,(H-h)$, where λ is a streambed-conductance term that must incorporate the hydraulic conductivity of the streambed, geometry of the streambed, and streambed thickness; H is the elevation of the water level in the stream; and h is the head in the aquifer at the streambed. As discussed by Hunt (1999), and emphasized by Rushton (1999), the head in the aquifer is assumed to remain in the streambed in this solution. (Solutions considering the case where the head in the aquifer drops below the streambed are discussed later.) This solution considers the impact of pumping on the head in the aquifer on the opposite side of the stream from the pumping well (fig. 1–1*C*). The solution yields the time-dependent response of the aquifer and for streamflow depletion to steady pumping from a well. Hunt (1999) shows how the solution presented approaches the Glover and Balmer (1954) solution as λ approaches infinity and the Hantush (1965) solution if λ is replaced by $2T/L$. Hunt (1999) points out that Hantush (1965) suggested that the distance from the stream to the well, d, in the solution may be varied to account for partial penetration of the stream (see also Jacob, 1950; and Spaulding and Khaleel, 1991) and that this suggestion appears to be incorrect. Evidently, the Hantush (1965) solution for the semi-infinite domain and fully penetrating stream may be used for the infinite domain and partially penetrating stream by appropriate correction to the retardation coefficient, L, using $L = 2T/\lambda$.

The notion that partial penetration of the streambed into the aquifer may be modeled by varying the distance from the well to the stream in the solution is not unique to Hantush (1965). Jacob (1950) suggested that the distance from the well to the stream may be varied in the Glover and Balmer (1954) solution to account for both streambed resistance and partial penetration of the streambed (Spaulding and Khaleel, 1991). To facilitate comparison of the analytical solutions, Spaulding and Khaleel (1991) used a three-dimensional analytical solution to derive a set of curves defining the effective distance from the well to the stream for different degrees of partial penetration for use in either the Glover and Balmer (1954) or Hantush (1965) solutions. Darama (2001) used this set of curves along with techniques from Wallace and others (1990) to examine cyclic pumping in the case of partially penetrating streambed with streambed resistance. Darama (2001) echoed the conclusions of Spaulding and Khaleel (1991) and Sophocleous and others (1995) that partial penetration of the streambed and streambed resistance are important factors in the solution that should be considered in the conceptual model.

Singh (2003) presents an alternate solution for a partially penetrating stream by adding an equivalent resistance length to the Hantush (1965) retardation coefficient to account for

[1] Streambed resistance in the paper by Hunt (1999) is L, but Hantush (1965) denotes this coefficient by a.

partial penetration. In this way the solution addresses both streambed resistance and partial penetration. An expression to approximate the additional resistance length that depends on the thickness of the aquifer and the stream width is provided. Singh (2003) also discusses the use of superposition to account for intermittent pumping. The geometry of the conceptual model is not discussed by Singh (2003), and the Hunt (1999) solution is not cited. Because of the relation between the Hantush (1965) and Hunt (1999) solutions, and because the Singh (2003) solution is an extension of the Hantush (1965) solution, there must be a relation between the Singh (2003) and Hunt (1999) solutions. This relation implies that the Singh (2003) solution could be used for the conceptual model shown in figures 1–1*B* or 1–1*C*. An analysis to relate the Hantush (1965) retardation coefficient, the streambed-conductance term used by Hunt (1999), and the resistance length added due to partial penetration in the Singh (2003) would be interesting but beyond the scope of this review.

Another approach to this conceptual model was offered by Zlotnik and Huang (1999), who derived an analytical solution by breaking the problem domain into two regions. The first region is the aquifer below the partially penetrating stream, and the second region is the adjacent semi-infinite aquifer. The solution is derived by simultaneously solving the equations for the two regions that are coupled by the boundary condition at the interface between the two regions. The solution is given as a Laplace Transform and is awkward to evaluate. A simplified version of the solution in which the storage coefficient in the region below the streambed is ignored yields a simpler solution that has a similar form to many of the other analytical solutions discussed. One advantage of this solution is that the stream has finite width in contrast to the solution presented by Hunt (1999) that models the stream as a line.

Butler and others (2001) extend the earlier work by Zlotnik and Huang (1999) and compare results of this analytical model to results from the solution presented by Hunt (1999) and to numerical results generated from MODFLOW. This analysis again emphasizes the importance of considering both partially penetrating streambed and streambed resistance when simulating the interaction between a pumping well and a stream. The authors noted that the model by Hunt (1999), which does not account for stream width, yields essentially the same result as a finite-width solution if the well is more than five stream-widths away from the stream. Comparison with the numerical model allowed the evaluation of the assumption that the aquifer is infinite in extent away from the stream. This analysis suggested that the aquifer width has to be hundreds of stream widths in extent before the analytical solution yields similar results as the numerical solution.

A solution for a finite-width stream also was given by Fox and others (2002). The nature of the solution and an alternate explanation for convergence problems identified by Fox and others (2002) is presented in the discussion by Hunt (2004). The difference between the finite-width solution (Fox and others, 2002) and line-width solution (Hunt, 1999) was investigated for a range of conditions. The difference depends on the distance from the well to the stream and the simulation time. When the well is more than 50 stream widths from the stream, the difference between the two solutions is less than 1 percent. In contrast to the findings of Butler and others (2001), the lower limit reported by Fox and others (2002) for agreement between the solutions is 25 stream widths. When the well is closer than 15 stream widths away from the stream, the maximum error between the solutions under the worst-case conditions is stated to be as great as 10 percent.

Di Matteo and Dragoni (2005a, 2005b) used MODFLOW to investigate partial penetration of the streambed into the aquifer and the impact of regional gradients on the solution. The importance of regional gradients for fully penetrating streams also was illustrated by Newsom and Wilson (1988), Wilson (1993), and Chen (2003). Di Matteo and Dragoni (2005a) present an interesting approach wherein MODFLOW was used to generate streamflow-depletion estimates, and then these estimates were fit by a nonlinear function in terms of the aquifer parameters and stream geometry. This empirical relation was then tested for a variety of conditions to illustrate the importance of anisotropy, partial penetration of the streambed, and the overlap between the bottom of the streambed and top of the well casing. This is the only paper that explicitly considers this overlap in the analysis.

Steady-state solutions to the partially penetrating streambed are presented by Ernst (1979) and Bakker and Anderson (2003). Ernst (1979) uses image-well theory to derive expressions for drawdown and streamflow depletion, but this paper appears to be largely forgotten because it is not often cited in the literature. Bakker and Anderson (2003) also use image-well theory and allow for a hydraulic gradient in the stream and for ambient flow in the aquifer at an arbitrary angle to the streambed. The solution is very interesting in that it illustrates the impact of pumping a well on the opposite side of the stream as solved by Hunt (1999) and schematically illustrated in figure 1–1*C*. In the special case of no hydraulic gradient in either the stream or in the aquifer (no ambient flow), the solution reduces to a steady-state evaluation of the solution by Hunt (1999). The Bakker and Anderson (2003) solution is similar in concept to that of Newsom and Wilson (1988) and Wilson (1993) except that it considers partial penetration of the streambed. The partial penetration of the streambed into the aquifer complicates matters and leads to a solution written in terms of complex potentials. As in the case of the earlier steady-state solutions, this solution is useful to delineate ultimate capture zones for wells and to distinguish between captured base flow and induced infiltration from the stream to the aquifer.

Partially Penetrating Stream With Drawdown in the Aquifer Below the Streambed

Several papers in the literature have discussed the importance of unsaturated flow in the analysis of the interaction of a stream and an aquifer when the head in the aquifer falls below the streambed and the stream becomes disconnected from the water table (perched). In all of the solutions presented earlier in this review, the head in the aquifer must remain within the streambed. In cases where the resistance to flow in either the aquifer or the streambed is large enough, the head in the aquifer may drop below the streambed in response to pumping. Classically, when the head in the aquifer falls below the streambed, the rate of streamflow depletion becomes constant and independent of the pumping rate. The rate of streamflow depletion depends on the water level in the stream, the elevation of the streambed, and the hydraulic characteristics of the streambed (as modeled in MODFLOW, for example (Harbaugh and others, 2000); see also the discussion by Rushton, 1999). Soil properties under unsaturated flow conditions, however, lead to more complicated behavior, and the rate of streamflow depletion also depends on the degree of saturation of the aquifer material below the streambed, the saturation-capillary pressure characteristics of the aquifer material, and the distance between the streambed and the water table.

Peterson and Zhang (2000) use a numerical model for unsaturated flow to demonstrate that the capillary pressure that develops below a perched stream may become an important consideration to the estimate of streamflow depletion. Solutions that use the classic approach described above may significantly underestimate the streamflow-depletion rate because they do not consider the flow from the stream to the aquifer caused by capillary-pressure differences and described by unsaturated flow theory.

Osman and Bruen (2002) recognized this problem and proposed a modified algorithm for losing streams for MODFLOW that includes a term to account for unsaturated flow. These authors compared the results of the modified MODFLOW model to a full unsaturated-flow model. They report that the modified approach performed much better than the classic MODFLOW approach compared to the unsaturated-flow model for the water-table configuration under a perched stream and for the estimated streamflow depletion. Bruen and Osman (2004) used Monte Carlo experiments to investigate the importance of unsaturated flow below perched streams and the heterogeneity of the underlying aquifer. They report that explicit consideration of aquifer heterogeneity compared to modeling with average properties increases in importance in the estimate of streamflow depletion when the water table is well below the streambed.

Fox and Durnford (2003) modify the Hunt (1999) solution to allow part of the stream to become perched. The segment of the stream that is perched delivers water to the unsaturated zone at a rate determined by the unsaturated properties of the aquifer, as described by the previous papers. Empirical testing allowed Fox and Durnford (2003) to generate an analytical-solution procedure. The authors showed that if the stream becomes perched, the drawdown is greater and streamflow depletion is less than that predicted by use of the Hunt (1999) solution, which does not allow the stream to become perched.

Streamflow Depletion in the Presence of Other Water Sources

The only water source for capture by the well to attain a steady state for all of the solutions presented thus far is the stream. The capture is either captured discharge from the aquifer that would have reached the stream or induced infiltration from the stream to the aquifer. The differences between the solutions are the rate that the system reaches steady state and the configuration of drawdown in the aquifer, such as whether the solution predicts drawdown on the side of the stream opposite from the pumping well. Other sources of water, however, may exist in some practical situations, and the estimate that ultimately streamflow depletion equals the pumping rate will not hold in these situations. Several papers present and analyze various other water sources (figs. 1–1*D* and 1–2).

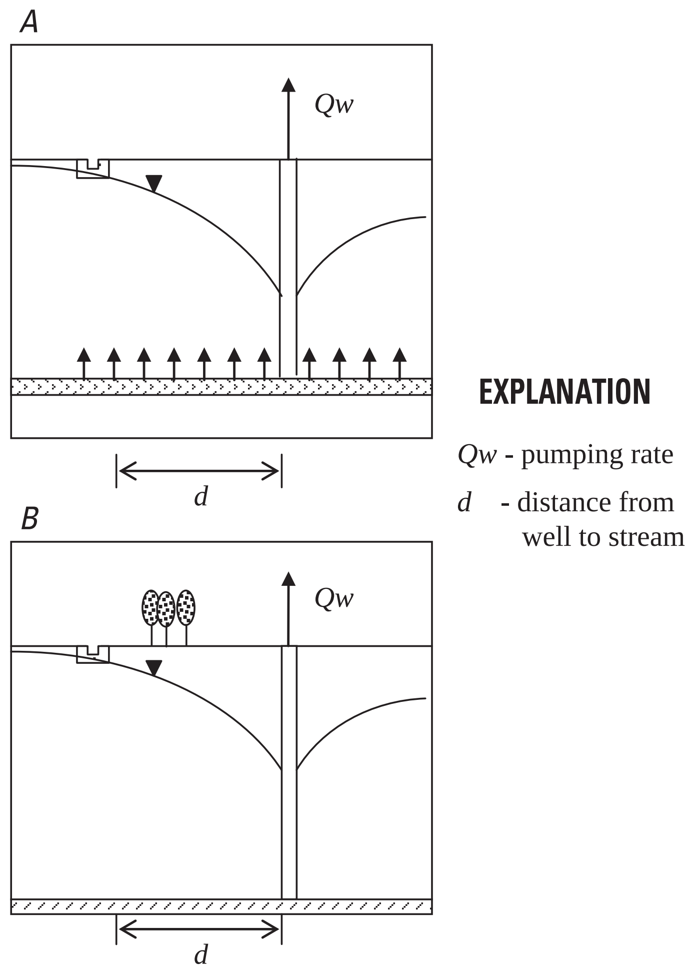

Figure 1–2. Alternate sources of water for capture by a well near a stream. *A*, Stream in an aquifer that overlies a regional aquifer with potentially different hydraulic properties. *B*, Stream in an aquifer system where pumping may interact with plants and change evapotranspiration losses from the system.

Hunt (2003a) presents an analysis for a stream in an semiconfining unit that overlies a leaky aquifer with a well (fig. 1–1*D*). Water may be released from storage from both the leaky aquifer and the semiconfining unit. The water released from storage from the semiconfining unit is the additional water source in this solution. The solution exhibits delayed-yield behavior: after an initial fairly rapid response to pumping, usually considered the result of the expansion of water and compression of the matrix, the response curve flattens for a time and then sharpens once again. The flattening of the response curve in this case is a result of the additional water source yielding water to the well without requiring additional drawdown in the aquifer. It is the only analytical solution to pumping a well near a stream that can fit this type of response by an aquifer. After long periods of time, as the system approaches a steady state, and the streamflow depletion will again equal the pumping rate. Release of water from storage from the semiconfining unit further delays the steady state such that the streamflow depletion may be less than the pumping rate for practical problems and time frames. In this conceptual model, the water in storage in the semiconfining unit is not recharged; therefore, the semiconfining unit cannot provide a long-term source of water to allow the system to reach steady state. This solution is used by several authors to analyze field data that exhibit delayed yield (Hunt, 2003b; Kollet and Zlotnik, 2003, 2005; Fox, 2004; and Lough, 2005).

Zlotnik (2004) solves a conceptual model that provides for a long-term source of water and generates a solution where the streamflow depletion rate is not necessarily the pumping rate at steady state. The conceptual model describes a stream in a shallow aquifer that overlies a deeper regional aquifer (fig. 1–2*A*). The shallow and regional aquifers may be separated by a confining or semiconfining unit. The regional aquifer presumably receives recharge that is independent of the stream and shallow aquifer and is modeled as maintaining a constant peizometric head. The conceptual model used for this analytical solution does not consider streambed resistance or partial penetration of the streambed into the shallow aquifer. The key result is that the streamflow depletion rate is dependent on the hydraulic properties of the shallow aquifer and the unit separating the shallow and regional aquifers. The paper also presents analysis of different boundary conditions for the shallow aquifer and summarizes test cases illustrating this type of behavior in the field.

Two papers investigated in interaction between pumping a well near a stream and changes in evapotranspiration losses from the aquifer (fig. 1–2*B*). Darama (2004) used analytical models, and Chen and Shu (2006) used the numerical model MODFLOW. Both of these papers illustrate how ground water may be captured by a reduction of evapotranspiration loss as the head in the aquifer is lowered by pumping. This evapotranspiration capture decreases the streamflow capture required for the system to reach steady state. Chen and Shu (2006) summarize two important points regarding this situation that depend on whether the issue is streamflow depletion in response to pumping or streamflow recovery in response to reductions in pumping. The first point is that the water captured by a reduction in evapotranspiration rate causes the streamflow depletion to be less than the pumping rate. The second point is that if pumping rates are reduced to help maintain streamflow, then the potential increase in evapotranspiration rates as the head in the aquifer is increased causes the increase in streamflow to be less than the reduction in pumping rate.

Application and Analysis of Streamflow-Depletion Models

Several articles and reports have been written that apply or analyze streamflow-depletion models. For this review, they are classified into two areas: application of the techniques to field problems and use of streamflow-depletion models for water-resources management. Most of the papers already cited provide application of the methods and discussion of the results. The papers in this section use the previous solutions or numerical methods that have already been summarized.

Application to Field Problems

Christensen (2000) demonstrated how the Hunt (1999) solution could be used to estimate streamflow-depletion parameters from aquifer-test data. This paper provides a detailed derivation of the inverse method and a discussion of the uncertainties associated with this type of analysis. The paper does not give an example of an application of the techniques to field data but refers to work that was later published by Nyholm and others (2002, 2003). Nyholm and others (2002) analyze two aquifer tests for wells located 60 m (200 ft) from a stream in a glacial outwash plain in Denmark. As discussed, the authors state that the conditions required to use the analytical solution by Hunt (1999) do not hold for these particular aquifer tests and use MODFLOW to simulate the tests. The inverse modeling code MODFLOWP (Hill, 1992) was used in this case (although MODFLOW–2000 should be able to produce similar results). The paper is notable in the analysis of the MODFLOWP information and related statistical tools and in the detailed discussion of this analysis. More detail regarding the tests and analysis of the test results, including the analysis of application of the Hunt (1999) solution, is offered by Nyholm and others (2003).

Hunt and others (2001) present an analysis of a field experiment that estimated the aquifer transmissivity and storage coefficient and the streambed-conductance factor by application of the Hunt (1999) solution to field data. (See also the discussion of the paper by Kollet and Zlotnik, 2002.) Hunt and others (2001) demonstrate the techniques used to estimate the aquifer and streambed properties.

Hunt (2003b) presents a short paper comparing application his 1999 model and his 2003 model to data from a field experiment. The brief paper demonstrates that the newer solution exhibiting delayed yield fits the field data better than the earlier solution, which does not include semiconfined conditions (Hunt, 1999). The newer solution fits over the entire time of the test and yields reasonable values for the aquifer characteristics.

Kollet and Zlotnik (2003) describe a detailed aquifer test near a stream with clusters of piezometers between a pumping well and a stream. They analyzed the data with both the Hunt (1999) and the Butler and others (2001) approaches. The authors argue that Butler and others' approach (2001) allows for a better fit of model parameters to the measured data because this model was better able to capture different hydrogeology at the site. Lough (2005) offers a different analysis of the data using the Hunt (2003a) model for a leaky aquifer exhibiting delayed yield and states that this approach better fits the entire response at the observation wells than does the late-time portion used by Kollet and Zlotnik (2003). Kollet and Zlonik (2005) reply that the aquifer is not leaky and suggest that the Hunt (1999; 2003a) analytical solutions do not fit the experimental data well because the assumption of horizontal flow (Dupuit assumption) is violated near the stream, as shown in the observation well data.

Chen and Chen (2003a) present another case study applying the Hunt (1999) solution to field data to estimate streamflow depletion parameters. The authors also present an ad hoc sensitivity analysis of the Hunt (1999) solution and an evaluation of the reliability of estimates for hypothetical cases. This paper received two comments in the literature stating that it did not recognize earlier work by Christensen (2000) or the application by Nyholm and others (2002). (See Christensen, 2005; Chen and Chen, 2005a.) Kollet (2005) argues that the Hunt (1999) solution was inappropriate for this field test and that Chen and Chen (2003a) did not adequately discuss the differences between their results and previously published work (see Chen and Chen, 2005b).

Fox (2004) presents another case study and compares the result of fitting the Hunt (1999), Butler and others (2001), Fox and others (2002), and Hunt (2003a) solutions to field data. In this case, the data again show a delayed-yield response, and the solution by Hunt (2003a) is claimed to fit the drawdown data the best (other fits are not shown). All of the methods were stated to adequately fit the late-time data obtained in the field, and the transmissivity values reported using each of the solutions were reasonable.

Use of Streamflow-Depletion Models for Water-Resources Management

The STRMDEPL program was first documented in a report describing the application of a precipitation-runoff model for the impact of water withdrawals on streamflow by Zarriello and Ries (2000). This implementation of the analytical solutions for streamflow depletion from wells was subsequently used in several other USGS studies in New England. Representative of these are two other precipitation-runoff models (Zarriello and Bent, 2004; Barbaro and Zarriello, 2007) and a detailed water-use and water-availability analysis (Barlow, 2003). In all four of these studies, STRMDEPL (Barlow, 2000) was used to estimate daily streamflow depletion based on daily pumping records from municipal wells. Streamflow depletion is delayed in time and attenuated compared with pumping records, and the analytical solution allowed the precipitation-runoff models to be appropriately calibrated to the pumping records.

A series of papers analyzed the proportion of streamflow depletion from induced infiltration from the stream to the aquifer and from captured discharge that would have reached the stream as base flow under different pumping or aquifer conditions (Chen, 2001; Chen and Yin, 2001; Chen and Shu, 2002; Chen and Chen, 2003b; and Chen and Yin, 2004). These papers, in addition to those by Newsom and Wilson (1988), Wilson (1993), and Bakker and Anderson (2003), may be used to assess water-quality issues arising from induced infiltration from the stream to an aquifer.

Chen and Yin (2001) and Chen and Shu (2002) use MODFLOW to study induced infiltration of stream water to an aquifer stressed by seasonally pumped wells. Chen and Shu (2002) emphasize streamflow depletion and the analysis of the depletion that continues after pumping is stopped. Chen (2001) uses particle tracking and a simple analytical model (Theis solution with an image well) to examine the capture zone of a well. Chen and Chen (2003b) use MODFLOW and particle tracking to assess the impact of anisotropy on the induced infiltration of stream water. Chen and Yin (2004) use the Hunt (1999) solution and apply the concepts illustrated by Wilson (1993) to identify the reach of stream where induced infiltration from the stream to the aquifer occurs. The ratio of capture by induced infiltration to total capture is presented for various conditions, and comparison of the analytical model results to numerical results generated with MODFLOW are presented. As discussed, distinguishing between induced infiltration and base-flow reduction is more important in water-quality analysis than in streamflow-depletion analysis because the total streamflow depletion is the same regardless of the partitioning between these mechanisms.

The Environment Agency, which manages water resources in England and Wales, evaluated potential ways to assess ground-water pumping on streamflow. The "Impact of Groundwater Abstractions on River Flows (IGARF I)" program was discussed by Kirk and Herbert (2002) and in technical reports by the Environment Agency (for example, Parkin and others, 2002).

Case studies examining whether reductions in pumping will change river flows form the core of a paper by Rushton (2002). The major message of this paper is that natural systems are more complicated than those described by most models and that careful hydrogeologic investigation and data collection are required to estimate whether ground-water pumping affects river flow at a given site. Rushton (2002) shows how the timing of recharge events, high and low flows, and seasonal changes in ground-water levels determine the response of the river to reductions in pumping when the river is at low flow. In some cases, Rushton argues, the pumping wells are virtually disconnected from the river during low flow and reductions in pumping may have only a marginal benefit on river flows.

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Appendix 2. Distribution of Withdrawal Between Neighboring Watersheds

A major aspect of the screening tool is the distribution of pumping between several neighboring valley segments. The simplest approach to estimate the impact of a proposed well on the stream network is to treat the withdrawal as a surface-water withdrawal and assume that the streamflow depletion due to pumping is immediate in time and entirely on the valley segment that drains the catchment containing the well. Use of the Hunt (1999) analytical model relaxes one of these assumptions and accounts for the delay in streamflow depletion due to removal of water from storage in the aquifer. All of the removal may be assigned to the valley segment in the catchment containing the well with no removal from other valley segments, but this approach is not physically realistic because a real well may capture water from adjacent valley segments. Because of the potentially complex geometry of the stream network, numerical ground-water-flow modeling would be required to rigorously estimate the capture from each valley segment. Keeping with the screening nature of the analysis; however, an approach to use an analytical solution was sought.

Wilson (1993) presented an analysis of streamflow depletion by pumping wells considering ambient flow to the stream. This analysis focused on steady-state solutions of induced infiltration from the stream to identify whether a well induced flow from the stream to the aquifer or whether the stream remained a gaining stream. In the latter case, pumping lowers the potentiometric level in the aquifer and reduces discharge to the stream but does not induce flow from the stream. This situation also may be described as capturing recharge that would have reached the stream in the absence of pumping. A solution is presented for a well between two parallel gaining streams (fig. 2–1).

The solution (Wilson, 1993) can be written as

$$Q_s = -2x'q_a + \frac{Q_w}{\pi}\cos^{-1}\left(\frac{1-\cosh\left(\frac{\pi x'}{L}\right)\cos\left(\frac{\pi d}{L}\right)}{\cosh\left(\frac{\pi x'}{L}\right)-\cos\left(\frac{\pi d}{L}\right)}\right), \quad (2\text{–}1)$$

where

- d is the distance from the well to one of two streams (length),
- x' is the distance along the stream from the point opposite the pumping well to the end of the zone of induced infiltration from the stream (length),
- cosh () is the hyperbolic cosine function (dimensionless),
- q_a is the ambient flow between the two streams per unit length of stream (length squared per unit time), and
- L is the distance between the two parallel streams (length).

Points x_s' and x_s are known as the stagnation points, and induced infiltration from the stream occurs along the distance *-x' to x'* (fig. 2–1).

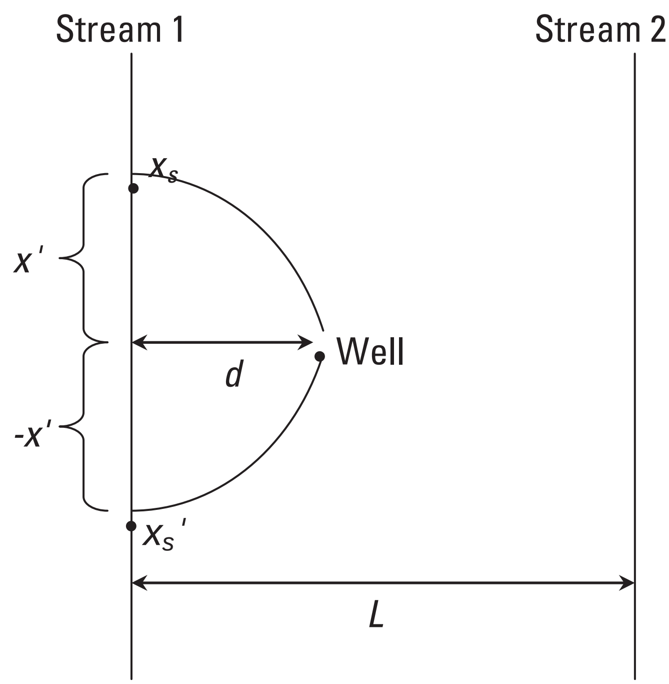

Figure 2–1. Pumping well between two parallel streams with notation used in the Wilson (1993) equation for steady-state streamflow depletion.

The ambient flow per unit length of stream, q_a, may be written as

$$q_a = \frac{NL}{2} + \frac{\Phi_2 - \Phi_1}{L}, \quad (2\text{–}2)$$

where

- N is the recharge rate (length per unit time),
- Φ_i is the state variable (length cubed per unit time) at stream i defined by,
- $\Phi_i = Th_i$ for a confined aquifer, or
- $\Phi = Kh_i^2$ for an unconfined aquifer,
- T is the transmissivity of the aquifer (length squared per unit time), and
- K is the hydraulic conductivity of the aquifer (length per unit time).

The stagnation point, x_s, is found by solving

$$\frac{Q_w}{2Lq_a} = \frac{\cosh\left(\frac{\pi x_S}{L}\right) - \cos(2\delta)}{\sin(2\delta)}, \qquad (2\text{–}3)$$

where

$$\delta = \frac{\pi d}{2L}. \qquad (2\text{–}4)$$

Details regarding the results from this solution are given by Wilson (1993). In summary, at low pumping rates, the well does not induce flow from either stream, and all of the well capture at steady state is from intercepted recharge. Determination of the percentage of this capture from recharge as diminishment of streamflow for each stream can be determined only through numerical ground-water-flow modeling (Wilson, 1993). As the pumping rate is increased, the well induces flow from the nearer stream and then from the second stream. At even higher pumping rates, as defined by the distance between the streams and the ambient flow between the streams controlled by recharge and aquifer conditions as shown in equation 2–3, the source of water to the well is dominated by induced flow from the two streams. At these higher pumping rates, the proportion of water induced by the pumping well from each stream depends only on the inverse of the distance from the well to each stream (Wilson, 1993). This last observation is used to guide the analysis for application of the analytical solution to multiple streams.

Distribution Methods Tested

Several methods based on either distances between a proposed well and the streams in the network or on the areas of the surface-water catchments associated with a proposed well, as approximations to the ground-water catchments, were tested to determine the most appropriate method to distribute water withdrawals between adjacent catchments in the screening tool. The methods distribute streamflow capture among adjacent or neighboring catchments defined as the valley-segment catchments that touch the boundary of the valley-segment catchment containing the proposed pumping well. Nine distribution methods were tested, and each method was computed by means of Python scripts that use geoprocessing commands (Tucker, 2005; van Rossum and Drake, 2006). The methods were inverse distance from valley segment, inverse distance from valley segment squared, inverse distance from catchment center, inverse distance from catchment center squared, transmissivity weighted, transmissivity weighted squared, natural neighbor, buffer around well, and no weighting. No weighting is the solution when all the streamflow depletion is assigned to the valley segment associated with the catchment containing the well.

Inverse Distance From Valley Segment

One distribution method, which is a direct extension of the analysis by Wilson (1993), is to assume that the distribution is directly proportional to the inverse distance from the pumping well to each stream. The contribution of any valley-segment catchment, *i*, is described by

$$f_i = \frac{\frac{1}{d_i^m}}{\sum_{j=1,n} \frac{1}{d_j^m}}, \qquad (2\text{–}5)$$

where

f_i is the fraction of the pumping attributed to valley segment *i*,

m is a factor to adjust weighting,

n is the number of adjacent valley-segment catchments, and

d_i is the distance from the proposed well to the closest point on the valley segment within catchment *i*.

To allow for close points to have greater influence on the contribution percentages, the factor *m* was included in the algorithm. Two methods of inverse distance weighting were tested: linear, *m*=1; and squared, *m*=2. Inverse distance squared weighting gives greater contribution to close valley segments compared to valley segments further from the proposed well than the linear inverse distance weighting.

Inverse Distance From Catchment Center

The philosophy of the Michigan statewide valley-segment framework is to group short arcs identified in the NHD dataset by hydrology and ecology into larger units. These larger units are the valley segments. Often, catchments associated with the valley segments contain several arcs for the same stream or arcs from different similar streams that join within the catchment. A second weighting scheme is based on this philosophy in that it uses the distance from the well to the adjacent valley-segment catchment centers to compute the contribution for each valley segment:

$$f_i = \frac{\frac{1}{l_i^m}}{\sum_{j=1,n} \frac{1}{l_j^m}}, \qquad (2\text{–}6)$$

where

l_i is the distance from the proposed well to the center of the valley-segment catchment *i*.

As in the previous case, inverse distance squared weighting also is implemented.

Transmissivity Weighted

The final distance-based weighting scheme uses the approach for computing the equivalent vertical hydraulic conductivity in a layered system. In this case, the transmissivity assigned to each valley-segment catchment also is used to weight the contribution from the catchment in combination with the inverse distance between the pumping well and the valley segment. Valley-segment catchments with low transmissivity will contribute less than adjacent catchments with higher transmissivity. The contribution for valley-segment catchment *i* is given by

$$f_i = \frac{\frac{T_i}{d_i^m}}{\sum_{j=1,n} \frac{T_j}{d_j^m}}, \tag{2–7}$$

where

T_i is the transmissivity assigned to valley-segment catchment *i*.

Again, inverse distance squared weighting is implemented for the testing.

Buffer Around Well

In contrast to the distance-based weighting schemes, two area-based schemes were developed. These methods were tested as options that may reproduce the interception of recharge by the pumping well better than the distance-based weightings. The first uses a circular buffer around the well to identify the potentially contributing valley-segment catchments. The fraction of the buffer area attributed to each catchment is used to determine the contribution for each valley-segment catchment. For this method, the size of the buffer is important. If the buffer is very small, then all the weight is assigned to the valley-segment catchment containing the well unless the well is quite close to the catchment boundary. If the buffer is too large, too many neighboring valley segments are assigned a fraction of the streamflow depletion, and the contribution from the catchment containing the well may be too low. To be consistent with the statewide screening, and to allow the hydrogeology of the setting to influence the estimate, a simple well drawdown computation with ad hoc values for drawdown, time, pumping, and storage coefficient was done to determine the buffer radius used in the computations. The Theis solution was used:

$$s = \frac{Q}{4\pi T} W(u) \quad , \quad u = \frac{Sr^2}{4Tt} \cdot \tag{2–8}$$

The equation was solved by bisection for each valley-segment catchment to determine the radius, *r*, for a drawdown, *s*, of 0.1 ft after 5 years of pumping, *t*, at 70 gal/min, *Q*, given the transmissivity, *T*, assigned to the valley-segment catchment in the screening tool, and a storage coefficient, *S*, of 0.1.

The contribution for each valley-segment catchment is given by

$$f_i = \frac{a_i}{\sum_{j=1,n} a_j}, \tag{2-9}$$

where

n is the number of adjacent valley-segment catchments, and

a_i is the area of the buffer enclosed by valley-segment catchment *i*.

Natural Neighbor

The final method uses natural neighbor weighting to compute the contribution from the adjacent valley-segment catchments. Natural neighbor weighting uses Theissen polygons to define the natural neighbors of the proposed well and to compute areal weighting for the well (Sibson, 1980, 1981). The points defining the Theissen polygons are the closest points from the well to the valley segments that are used in the analytical solution. Natural neighbor weighting is computed by first generating a set of Theissen polygons for these points. A second set of Theissen polygons is then created with the closest valley-segment points and the well location. The overlap between these two sets of polygons is used to estimate the weighting assigned to each of the valley-segment points. If the new polygon generated around the well does not overlap with some of the original Theissen polygons, then the weight assigned to the points in these polygons is zero. If the well falls exactly on one of the valley-segment points, which means that the well is placed on a valley segment, the polygon generated in the second step exactly overlaps one polygon from the first set and the weight assigned to this point is 1. The contribution for each valley-segment catchment is given by

$$f_i = \frac{a_i}{\sum_{j=1,n} a_j}, \tag{2–10}$$

where

a_i is the area of influence determined by means of the overlapping areas of the Thiessen polygons for each of the natural neighbors.

The analytical model by Hunt (1999) was used to compute the time-dependent streamflow depletion due to a pumping well. This model provides the fraction of the pumping rate attributed to removal from storage and to streamflow capture. The pumping from a proposed well is distributed between adjacent valley segments by estimating a contribution for each valley-segment catchment. These contributions are assumed to be valid for the entire pumping time for the well. To estimate streamflow depletion for each of the valley segments, the analytical solution is computed for the well and each valley segment independently. These solutions are multiplied by a fraction representing the contribution to the pumping well for each valley-segment catchment. The sum of the contributions from each valley segment must equal 1 so that the sum of the streamflow depletions for all the contributing valley-segment catchments is equal to the pumping rate as the system reaches steady state. To compute the analytical solution for each valley segment, the distance between the closest point on the valley segment and the proposed well is determined. This distance is used along with the aquifer properties of the catchment containing the well to compute the streamflow depletion with time.

Testing Procedure

The ground-water-flow model for the area around Kalamazoo County, Mich. (Luukkonen and others, 2004) was used to test the distribution methods. The ground-water-flow model is a finite-difference (MODFLOW) simulation model with 6 layers, 154 rows, and 162 columns. MODFLOW is documented by Harbaugh and others (2000). The smallest grid spacing in the model is 660 ft by 660 ft. Valley-segment catchments in the interior of the model that have this finest grid spacing were used in the methods testing. To illustrate the applicability of the analytical model to field problems, a transient simulation with seasonally varying recharge and pumping rates was used as the test case. Luukkonen and others (2004) presented the results for a 9-year transient simulation; but, in this work, the length of the simulation was reduced to 5 years to reduce computer run time.

A method to illustrate streamflow capture by pumping wells (Leake and Reeves, 2008) was used to examine the spatial distribution of streamflow capture from the valley segments. In this method, hypothetical wells are added to the MODFLOW model sequentially on a grid of cells (fig. 2–2). One well is added to a specified cell, and the new simulation is computed. The results from this new simulation are subtracted from base-model results to determine the capture and change in storage caused by the new well. The process is repeated with one new well at a time, generating a grid of results that may be mapped. The fluxes to individual river cells representing the valley segments from the statewide data framework were computed. These fluxes were recorded by use of a river observation file (Hill and others, 2000) to designate the finite-difference cells assigned as river cells to the appropriate valley segments. The river flux output from the system with the new well for each designated valley segment was subtracted from the valley-segment flux computed with the original model to yield the streamflow depletion due to the new well as simulated with the MODFLOW model. Values for streamflow depletion as a percentage of pumping rate for the grid of wells shown in figure 2–2 placed in layer 3 of the model were interpolated by means of inverse distance weighing to produce the map shown in figure 2–3. These streamflow depletions and the spatial pattern produced through this technique are used to access the distribution schemes applied with the analytical model.

The analytical model was solved for the same grid of points as the MODFLOW model illustrated in figure 2–2. Python scripts for the distribution methods used geoprocessing commands (Tucker, 2005; van Rossum and Drake, 2006) to identify the catchment containing the well, to identify the neighboring catchments, and to compute the different weightings. The analytical solution was computed for the well and each of the nearby valley segments sequentially by use of the transmissivity assigned to the valley-segment catchment containing the test point, which for these trials was always valley-segment catchment 3544. The storage coefficient and streamflow-conductance terms for this catchment from the water-withdrawal screening tool also were used.

The streamflow depletion for each valley segment and each distribution method was estimated by multiplying the analytical solution for that valley segment-test point combination by the computed percent contribution for the valley-segment catchment. The resulting streamflow depletions were compared to the depletions computed with the MODFLOW model through the river observation file (Hill and others, 2000) for each valley segment. The results from the ground-water-flow model and the analytical solutions after 5 years were compared to ensure that differences in the solutions resulting from differences in the storage coefficient used in the screening tool and the MODFLOW model do not dominate the analysis. To avoid problems with differences between small estimates of streamflow depletion biasing the analysis, the difference between the MODFLOW results and the analytical model was computed only if either the MODFLOW or the analytical model estimated a streamflow depletion of 5 percent of the pumping rate or greater.

The simplest approach for the screening procedure would be the no-weighting approach. The capture caused by a proposed well would be assigned to the valley segment in the catchment containing the well. In essence, use of this approach assumes that the ground-water divides are coincident with surface-water divides and that the divides do not change in response to pumping. Because ground-water divides will respond to pumping, this should be a poor assumption. Testing reveals that streamflow depletion was overestimated in this approach compared to the MODFLOW model results (figs. 2–3 and 2–4). The minimum streamflow depletion estimated by way of this approach is approximately 63 percent, and the estimated streamflow depletion is greater than 80 percent for much of the valley-segment catchment. These results do not compare well with results generated using the MODFLOW model. For the MODFLOW model, the maximum estimated streamflow depletion for the valley segment was less than 80 percent for most of the catchment and it was less than 20 percent for parts of the valley-segment catchment near the most distant surface-water divides defining the catchment. On the basis of this comparison, the no-weighting approach—although computationally the most straightforward method—was rejected as an option for the screening model.

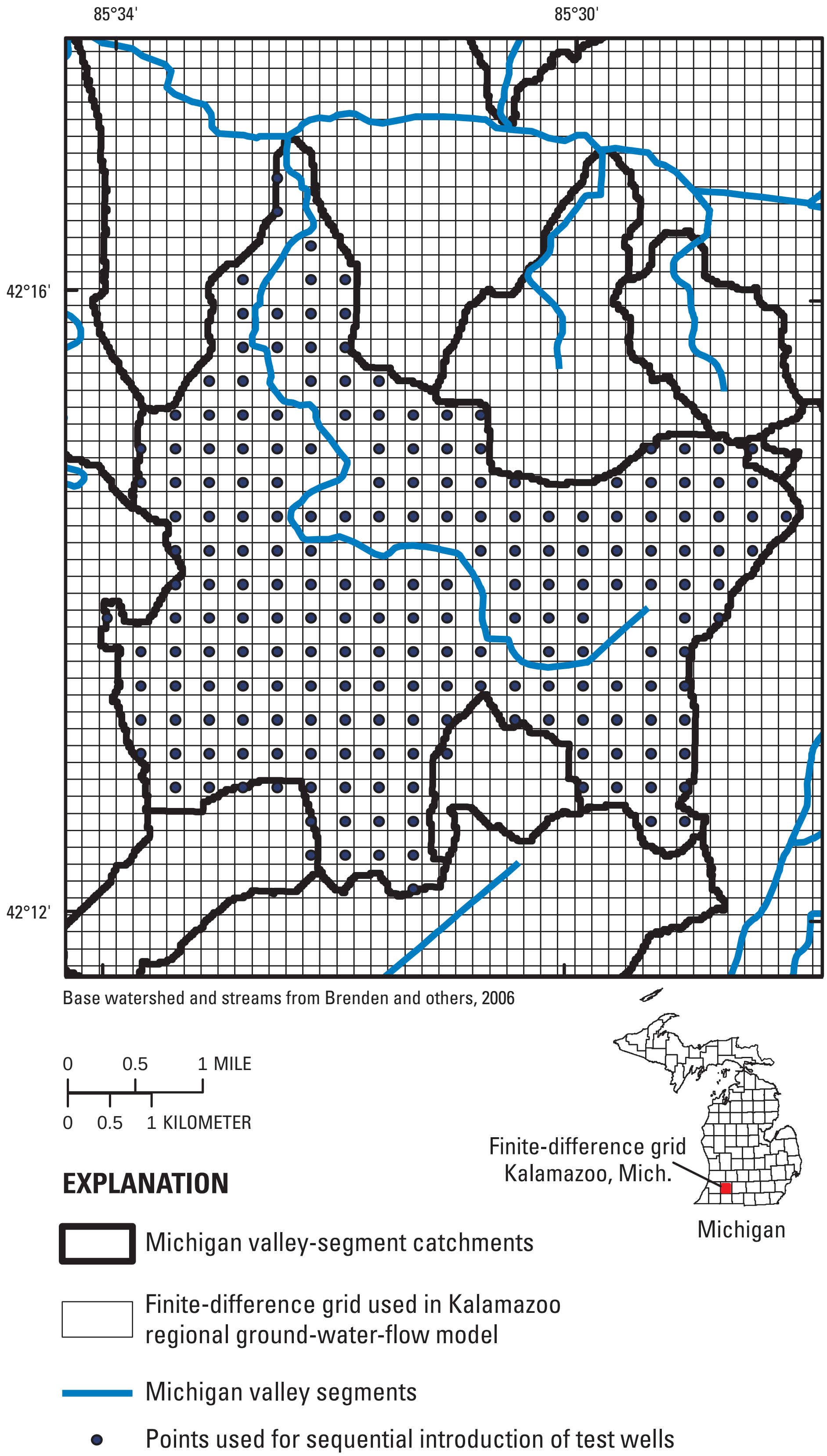

Figure 2–2. A grid of points used to compare the analytical model and different distribution methods to MODFLOW results from the Kalamazoo regional ground-water-flow model.

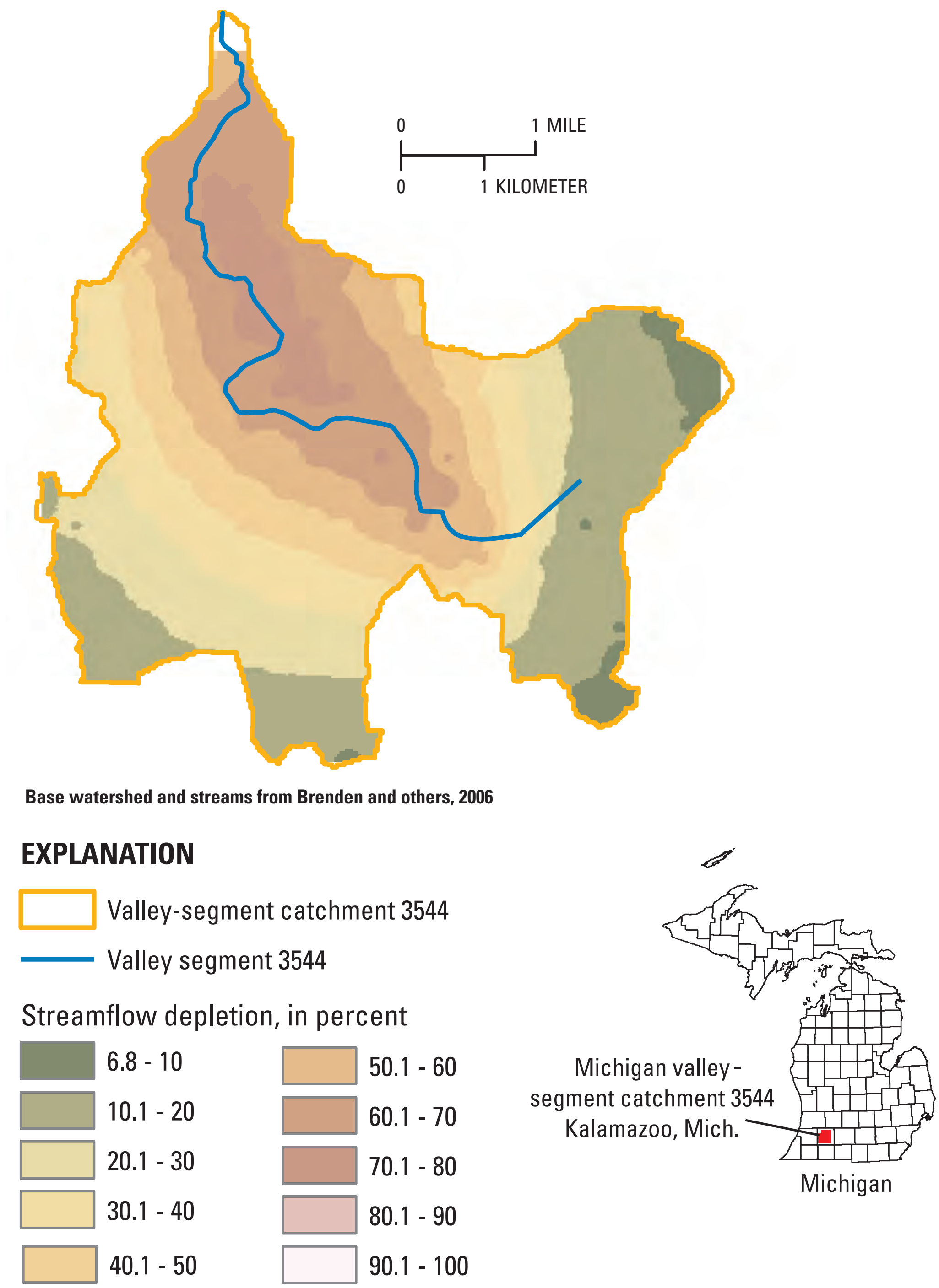

Figure 2–3. Estimated streamflow depletion from valley segment 3544 resulting from a sequential introduction of test wells in the MODFLOW ground-water-flow model for Kalamazoo County, Mich., as a percentage of pumping rate after 5 years of pumping.

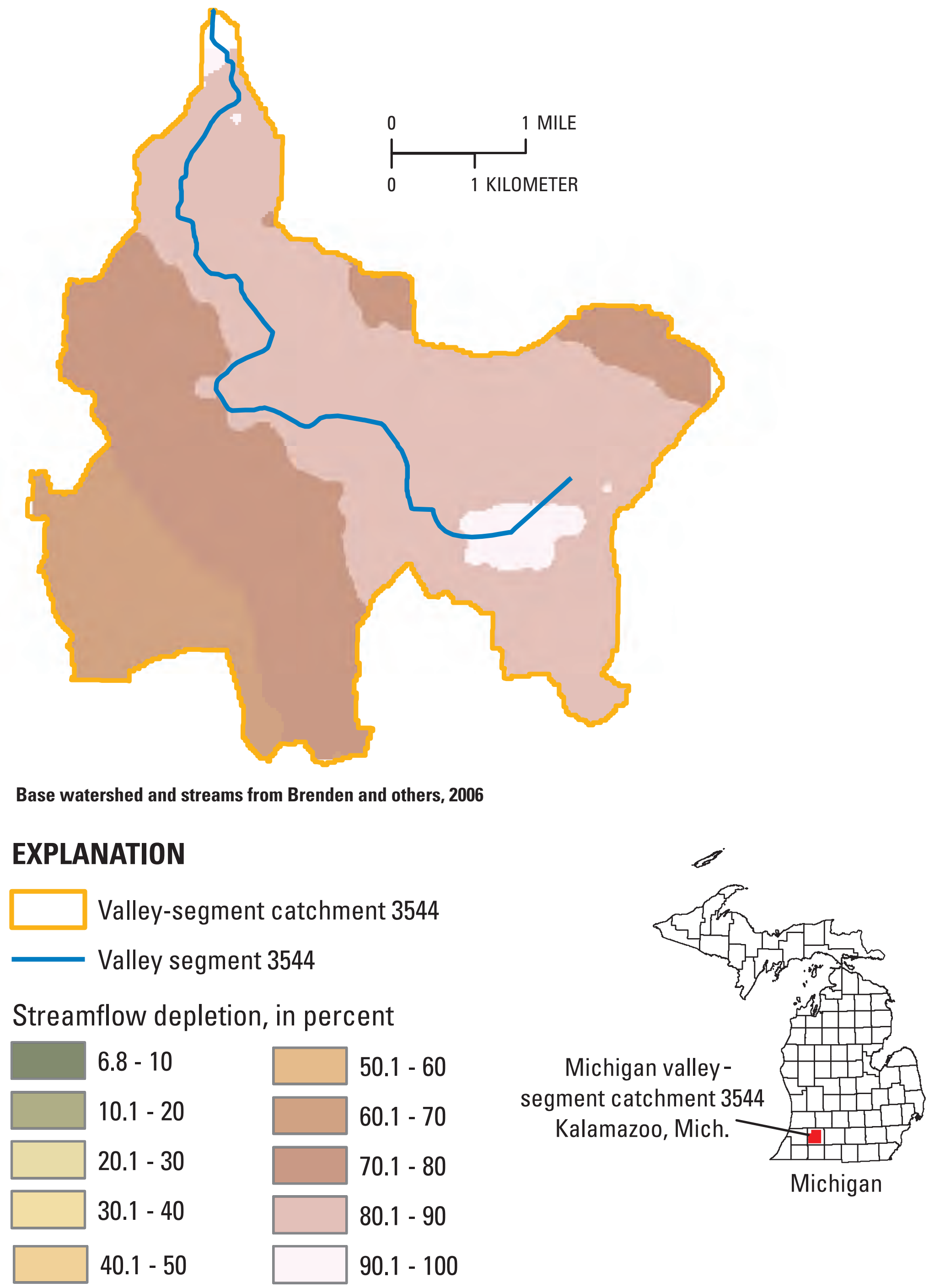

Figure 2–4. Estimated streamflow depletion from valley segment 3544 resulting from a sequential application of the analytical model to test wells with no weighting approach between adjacent valley segments as a percentage of pumping rate after 5 years of pumping.

The distribution approaches that matched the MODFLOW results the best were the inverse distance to valley segment, inverse distance to valley segment squared, and natural neighbor weightings (fig. 2–5). The inverse distance to valley segment squared and natural neighbor approaches overestimate streamflow depletion compared to the MODFLOW results, and the inverse distance to valley segment weighting tends to underestimate the depletion near the stream compared to the MODFLOW results. The transmissivity-weighted approaches (not shown) are not significantly better than the inverse distance to valley segment weightings and require slightly more computational effort and more book-keeping to gather and use the transmissivity of each neighboring valley-segment catchment. The buffer weighting and distance to center weighting (also not shown) did not produce interpolated maps that were reasonable matches to the MODFLOW results, and these methods were rejected. Statistical and ranked comparisons of the weighting methods based on the differences between each method and the MODFLOW results showed that each of the methods performed the best for some of the hypothetical well points and were outperformed at others. None of the methods produced a statistically significant difference in error characteristics compared with the MODFLOW results to help guide the decision. As a result of this testing, the inverse distance to the valley segment method was selected for the screening tool because it produces a reasonable overall pattern of streamflow depletion compared with the MODFLOW tests, it is the most straightforward to implement in the Web application, and it has some theoretical basis in Wilson's analysis (1993).

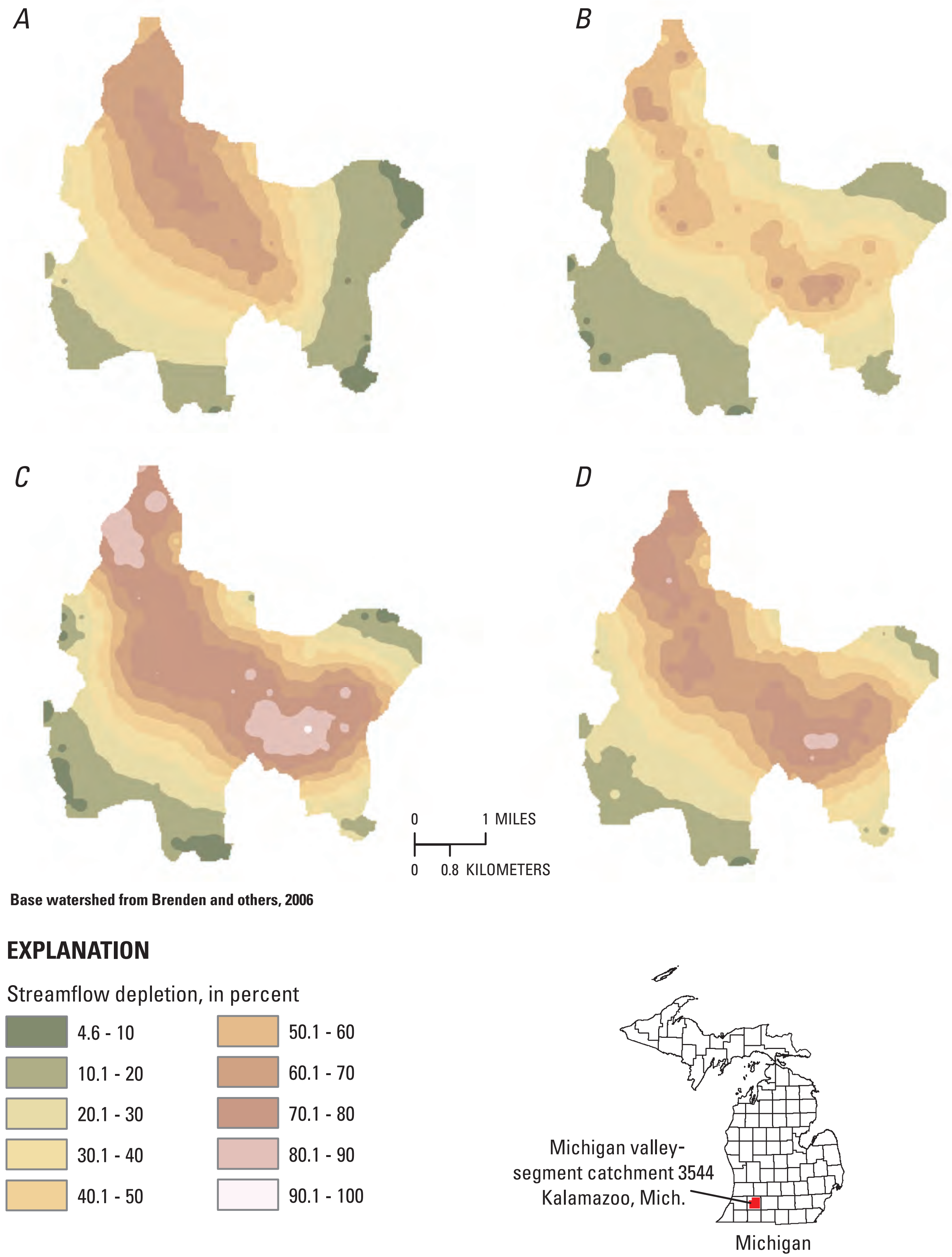

Figure 2–5. Estimated streamflow depletion from valley segment 3544 as a percentage of pumping rate after 5 years of pumping. ***A***, results from a sequential application MODFLOW. Results from sequential application of the analytical model with ***B***, the inverse distance to the stream, ***C***, inverse distance to the stream squared, and ***D***, natural neighbor distribution methods.

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